

Department of Food Technology
University of Helsinki

EKT series 1380

Role of heat treatment in the processing and quality of oat flakes

Fred Gates

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Agriculture and Forestry of
the University of Helsinki, for public examination in lecture room B2 at Viikki

on 16 May 2007, at 12 noon.

Helsinki 2007

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ISBN 978-952-10-3907-2 (pbk.)

ISBN 978-952-10-3908-9 (PDF)

ISSN 0355-1180

Yliopistopaino

Helsinki 2007

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Fred Gates (2007): Role of heat treatment in the processing and quality of oat flakes. EKT series 1380. University of Helsinki, Department of Food Technology, 69 pp.

Abstract

This thesis reports on investigations into the influence of heat treatment on the manufacturing of oat flakes. Sources of variation in the oat flake quality are reviewed, including the whole chain from the farm to the consumer. The most important quality parameters of oat flakes are the absence of lipid hydrolysing enzymes, specific weight, thickness, breakage (fines), water absorption. Flavour, colour and pasting properties are also important, but were not included in the experimental part of this study. Of particular interest was the role of heat processing. The first possible heat treatment may occur already during grain drying, which in Finland generally happens at the farm. At the mill, oats are often kilned to stabilise the product by inactivating lipid hydrolysing enzymes. Almost invariably steaming is used during flaking, to soften the groats and reduce flake breakage.

This thesis presents the use of a material science approach to investigating a complex system, typical of food processes. A combination of fundamental and empirical rheological measurements was used together with a laboratory scale process to simulate industrial processing. The results were verified by means of industrial trials.

Industrially produced flakes at three thickness levels (nominally 0.75, 0.85 and 0.90 mm) were produced from kilned and unkilned oat groats, and the flake strength was measured at different moisture contents. Kilning was not found to significantly affect the force required to puncture a flake with a 2mm cylindrical probe, which was taken as a measure of flake strength.

To further investigate how heat processing contributes to flake quality, dynamic mechanical analysis was used to characterise the effect of heat on the mechanical properties of oats. A marked stiffening of the groat, of up to about 50% increase in storage modulus, was observed during first heating at around 36 to 57°C. This was also observed in tablets prepared from ground groats and extracted oat starch. This stiffening was thus attributed to increased adhesion between starch granules.

Groats were steamed in a laboratory steamer and were tempered in an oven at 80 – 110°C for 30 – 90 min. The maximum force required to compress the steamed groats to 50% strain increased from 50.7 N to 57.5 N as the tempering temperature was increased from 80 to 110°C. Tempering conditions also affected water absorption. A significantly higher moisture content was observed for kilned (18.9%) compared to unkilned (17.1%) groats, but otherwise had no effect on groat height, maximum force or final force after a 5 s relaxation time.

Flakes were produced from the tempered groats using a laboratory flaking machine, using a roll gap of 0.4 mm. Apart from specific weight, flake properties were not influenced by kilning. Tempering conditions however had significant effects on the specific weight, thickness and water absorption of the flakes, as well as on the amount of fine material

(<2 mm) produced during flaking. Flake strength correlated significantly with groat strength and flake thickness. Trial flaking at a commercial mill confirmed that groat temperature after tempering influenced water absorption. Variation in flake strength was observed, but at the groat temperatures required to inactivate lipase, it was rather small. Cold flaking of groats resulted in soft, floury flakes.

The results presented in this thesis suggest that heating increased the adhesion between starch granules. This resulted in an increase in the stiffness and brittleness of the groat. Brittle fracture, rather than plastic flow, during flaking could result in flaws and cracks in the flake. These would be expected to increase water absorption. This was indeed observed as tempering temperature increased. Industrial trials, conducted with different groat temperatures, confirmed the main findings of the laboratory experiments.

The approach used in the present study allowed the systematic study of the effect of interacting process parameters on product quality. There have been few scientific studies of oat processing, and these results can be used to understand the complex effects of process variables on flake quality. They also offer an insight into what happens as the oat groat is deformed into a flake.

Preface

The work was carried out at the Department of Food Technology of the University of Helsinki. The work started in 1999 as a project funded by the Ministry of Agriculture and Forestry and Myllyn Paras Ltd. In 2000 the Finnish Food and Drink Industries' Federation funded a three month stay at the University of Reading. Funding from Tekes industrial R & D grants to Helsinki Mills Ltd. and Myllyn Paras Ltd. enabled this work to be completed. I am grateful for all the financial support that has enabled me to carry out this work.

I thank my supervisor Professor Hannu Salovaara, for giving me this project and providing the facilities and funding. I am also grateful to Dr. Bogdan Dobraszczyk for freely giving so much of his time to teach me about mechanical properties and to comment on my manuscripts. I thank Dr. Tuula Sontag-Strohm for all the friendly advice and support that I have received since my days as an undergraduate student. I thank Fred Stoddard for getting “professorial” with me, his support and advice was invaluable in bringing this work to completion. I also want to thank Professor Yrjö Mälkki and Professor Yrjö Roos for reviewing this thesis, your comments were very helpful .

People from the oat industry have also been willing to share information on the process. In particular I wish to thank Myllyn Paras Ltd. for getting things started, in particular Simo Zuban and later Jarkko Arrajoki for their valuable practical insights into the oat flaking process. I am grateful also to Helsinki Mills Ltd., who joined the project a little later and in particular Raimo Keskinen, Erkki Pöytäniemi and Ilkka Kahilakoski, the information you shared enabled me to focus. To Colin Browne and Harry Baillie from Quaker Oats Ltd. for interesting discussions and allowing me to visit the mill in Cupar, Scotland. I am also grateful for the samples and advice provided by Pirjo Peltonen-Sainio and Marketta Saastamoinen.

I am thankful to Marika Hautala, Mirkka Sohlberg and Alexandra Shilenko, who helped me by carrying out some of the experiments for their thesis work. I thank Riku Talja for helping me with the DMA work, and for all the discussions that we have had. I also wish to thank all my colleagues (past and present) at the department for the good working atmosphere. In particular I would like to thank Markku Mikola, Heli Anttila and Jussi Loponen for helping me out in so many ways (especially with writing Finnish) and Tiina Kaarlehto for advice based on her long experience in researching oat technology. My friends and family have been very supportive, without them none of this would have been possible. Finally, I wish to thank my wife Laurence for her love and support.

Fred Gates

Helsinki

List of original papers and contributions of the authors

- I. Gates, F. K.; Dobraszczyk, B. J.; Salovaara, H. Influence of some processing and storage conditions on the mechanical properties of oat flakes. *Trans. ASAE* **2004**, *47*, 223-226.
- II. Gates, F. K.; Talja, R. A. Effect of temperature and moisture on the mechanical properties of oat. *Trans. ASAE* **2004**, *47*, 1223-1227.
- III. Gates, F. K., Dobraszczyk B. J., Stoddard, F. L., Sontag-Strohm, T., Salovaara, H. Interaction of Heat-Moisture Conditions and Physical Properties in Oat Processing: I. Mechanical Properties of Steamed Oat Groats. (Manuscript accepted for publication in *Journal of Cereal Science*).
- IV. Gates, F. K., Stoddard, F. L., Dobraszczyk B. J., Sontag-Strohm, T., Salovaara, H. Interaction of Heat-Moisture Conditions and Physical Properties in Oat Processing: II. Flake Quality. (Manuscript submitted to *Journal of Cereal Science*).

The publications are referred to in the text by their Roman numerals.

	I	II	III	IV
Original idea	HS/FG	FG	FG	FG
Design of experiments	FG	FG	FG	FG
Data Analysis	FG	FG/RT	FG/FS	FG/FS
Manuscript preparation	FG/BD	FG	FG/FS BD/TSS/HS	FG/FS BD/TSS/HS

Hannu Salovaara was the responsible supervisor, Bogdan Dobraszczyk also supervised this work.

Abbreviations

A_w	Water activity
BET	Brunauer–Emmett–Teller isotherm model
DMA	Dynamic mechanical analysis
DSC	differential scanning calorimetry
E'	storage modulus
E''	loss modulus
GAB	Guggenheim–Anderson–de Boer isotherm model
RH	Relative humidity
RVA	Rapid viscoanalyser

1. Introduction

Oat is an important cereal crop in Finland, rivalled only by barley. Indeed, Finland is a leading exporter, competing with Sweden for second place as the largest oat exporter after Canada. The interest in the link between diet and health, in particular the ability of the soluble fibre of oat to lower serum cholesterol, has increased interest in oats. However, most oat exports are in the form of a low value, agricultural commodity. Processing in Finland is needed to increase the value of the oat crop.

The export of food products is difficult because preferences vary between countries, and even regionally within countries. Furthermore, consumers often prefer locally produced foods. Consumer markets for products such as porridge flakes and ready-to-eat breakfast cereal tend to be dominated by established brands. Nevertheless, there is a market for oat ingredients, such as oat bran, flour and flakes, but these products must be competitive both in quality and price.

Previous studies had shown that cultivar, environmental conditions and processing parameters all affect flake quality (Molteberg et al., 1996; Doehlert and McMullen, 2000; Lapveteläinen et al., 2001; Rhymer et al., 2005). A long-term breeding programme, combined with favourable growing conditions and a well-developed infrastructure for the post-harvest treatment of oats, ensure high quality and a good reputation internationally. A challenge for Finnish businesses attempting to enter foreign markets with an oat ingredient is that the quality expectations may differ from those in Finland.

There are no widely accepted definitions of oat flake quality, or how it is to be measured. Considerable variation exists in the size, thickness, colour, pasting behaviour and water absorption of flakes that are available. Furthermore, there is little knowledge on how to achieve a product which matches all aspects of the specification.

Two heat treatments are commonly used in oat processing. The first, kilning, is to stabilise the oat. The second, referred to in this thesis as steam tempering is to soften it during flaking. Whilst the effect of heating on oat starch, soluble fibre, protein and nutritionally important constituents has been studied to some extent, there have been few technological studies. Molteberg et al. (1996) studied the effect of heat processing on the flavour and storage stability of oats, by steaming pre-moistened oats at 100°C for 10 minutes and then drying at 100°C in an oven. Oeding (1996) studied the effect of hydrothermal treatment on the physical and physicochemical properties of oat flakes using a response surface methodology, with three variables (steam temperature, time and product moisture). Lapveteläinen et al. (2001) reported an extensive study using industrial conditions, but some of the key data presented, such as cultivar names, were coded.

The aim of this study was to elucidate the effect of heat treatments on the quality of oat flakes. Since ensuring the stability of oat flakes is not a problem for industrial mills, other parameters such as flake texture and water absorption were taken as measures of flake quality. More experimental objectives are given later.

2. Literature review

The quality of oat products is dependent on a chain of factors that starts at the farm and extends through milling and possibly other additional industrial processing (e.g. muesli or biscuit making) to the consumer. In the absence of other constraints, yield is the most important consideration for the farmer. Total yield is, however, an over simplification and the definition of yield needs to bear in mind the end use of the oats. Since the oat caryopsis (referred to as the groat) does not generally thresh free from the lemma and palea, the hull content has to be considered. Since ancient times there have been cultivars that thresh free from the hulls, and these are known as naked oats. Except in the case of naked oats, the removal of hulls is essential in oats destined for food-uses. Thus, the milling yield or the amount of unbroken groats are more important to the end user than total yield (Doehlert et al., 1999; Groh et al., 2001).

The floral structure of the oat plant is in the form of an open panicle, with spikelets at the ends of the branches. The spikelets can bear up to three kernels, the largest of which is termed the primary kernel and the smallest the tertiary kernel. Sometimes the primary kernel does not develop, giving rise to a double or bosom oat (Youngs et al., 1982; White, 1995), this seems to be mostly influenced by genetic factors but environmental factors also have a role (Doehlert et al., 2002). For industrial processing, a uniform size distribution is desirable.

Generally, cereal quality is considered in terms of chemical indicators, for example protein, starch and moisture contents. In this work, emphasis is given to the physical determinants of quality, in particular the mechanical properties. These are closely related to the structure of the groat, which has been described in detail by Fulcher (1986). Oat groats, like other cereal grains, have a cellular structure the majority of these are so called starchy endosperm cells. The starchy endosperm is surrounded aleurone layers and the pericarp. The germ is located at one end of the groat, and is separated from the endosperm by the scutellum. The endosperm cell differ from wheat, in that the starch granules are not surrounded by a continuous protein matrix, but the protein is present in the form of discrete bodies. Also the cell walls in the oat endosperm are mostly intact, and contain beta-glucan.

2.1. On farm factors that affect oat flake quality

2.1.1. Genetic and environmental factors

Genotypic variation in yield exists, however environmental factors also have a

strong influence on both yield and quality and interactions between these factors (Doehlert and McMullen, 2000; Browne et al., 2003). Some environmental factors, such as the weather, are beyond the control of the farmer, but agronomic practices such as the application of nitrogen or higher seed rates can increase overall yield. Nevertheless in some experiments, these treatments resulted in a lower groat yield (Browne et al., 2003). It is also vital to bear in mind this distinction between oats and groats whenever considering oat quality. The composition of the hull and the groat differ, and contaminants (e.g. residues or mycotoxins) may not be evenly distributed. Genetic and environmental factors can also affect other quality characteristics, such as the shape and size of the groat (Symons and Fulcher, 1988a), which can influence hullability.

Despite the advantages both for feed and food, naked oats have never gained much popularity, representing only about 0.1% of the total oat acreage in Finland (Peltonen-Sainio et al., 2004a). This can be accounted for by the partial retention of hulls, lower viability of naked oats and issues with storage stability that result from damage to the unprotected groat (Peltonen-Sainio et al., 2004a). Despite concerns that mechanical damage during harvest would reduce the stability of groats, only slight oxidation of linoleic acid was observed over a period of two years (Kirkkari et al., 2004). For undamaged groats, lipase activity actually decreased during storage (Sahasrabudhe, 1982). This confirmed an earlier study showing that under cool, dry conditions, hulled and hullless oats are equally stable during storage (White et al., 1999). A more serious problem for the food industry is the significant hull content of naked oats that ranges from about 0.7% to 13% (Peltonen-Sainio et al., 2004a). In particular, small groats tend to retain the hulls, during both threshing and impact hulling, which appeared to be related to grain filling rather than maturity (Kirkkari et al., 2004; Peltonen-Sainio et al., 2004b). Solutions for the problem may lie in a combination of plant breeding and improved separation procedures on the farm.

In Finland, the quality of oats is systematically monitored by Agrifood Research Finland (MTT) and the Food Safety Agency (Evira), and this information is potentially useful to millers. There are clear differences between cultivars in milling yield (Doehlert et al., 1999) and in the quality of flakes (Molteberg et al., 1996; Lapveteläinen et al., 2001; Rhymer et al., 2005). There are also differences in the chemical composition of cultivars, both for constituents that are desirable for human health, such as mixed linked (1 \rightarrow 3) (1 \rightarrow 4)- β -D-glucan, hereafter referred to as beta-glucan (Saastamoinen et al., 1992; Saastamoinen et al., 2004), as well as for mycotoxins (Hietaniemi et al., 2004) and heavy metals, such as cadmium (Eurola et al., 2003). One reason that millers are not making more use of differences between cultivars seems to be that greater differences are often observed between samples of the same cultivar grown in different years and at different locations, than those between cultivars. Significant sources of variation are even found within a single

cultivar grown in a particular location. For example, one study showed that location, genotype, kernel type (i.e. primary, secondary or tertiary) and panicle position influenced kernel weight (Doehlert et al., 2002).

Composition is also determined by both cultivar and environmental factors, and this affects the nutritional and technological quality of the products. Soluble fibre, in particular β -glucan, is currently the main constituent of interest. A Finnish study showed that high β -glucan content was associated with large groat size and low protein content (Saastamoinen et al., 1992). However, in a study in the USA β -glucan was not associated with groat protein content, but negatively correlated with starch content (Doehlert and McMullen, 2000). In the UK, a positive relationship between β -glucan and protein within a cultivar (Welch et al., 1991), although the same group had previously shown no significant correlation with protein across cultivars (Welch and Lloyd, 1989). This illustrates the complex interaction between factors that determine quality. The variation in composition also related to milling characteristics, including breakage during the hulling process (Doehlert and McMullen, 2000). These will be dealt with in more detail later, in the context of the oat hulling process.

2.1.2. Interactions with other organisms

The interactions between oats and other organisms in relation to quality should not be neglected. Diseases, such as crown rust (*Puccinia coronata*), can affect many quality characteristics of oats, including groat breakage during hulling (Doehlert and McMullen, 2000). Some cultivars are more susceptible to infection than others (Doehlert and McMullen, 2000). Although this fungal disease is prevalent in the Americas (Leonard, 2000; Galbraith, 2004), it does not seem to be as significant in northern Europe. Weeds can also adversely affect oat quality in the field. Wild oats (*Avena fatua*) are difficult to separate from oats and cause an increase in hull content, thus reducing the quality and the price of the oats. The use of crown rust as a biological control agent for wild oats has been suggested (Johnston et al., 2000), but the risks to oat quality also need to be considered.

As well causing loss of yield, parasitic fungi that infect cereals in the field may produce toxic metabolites. These toxins, known as mycotoxins, may also be produced by saprophytic fungi that colonise grain during storage. The key limiting factors for fungal growth are available water and temperature, whereas mechanical damage to the grain increases the susceptibility to fungal invasion (Lacey and Magan, 1991). Colonisation by fungi does not necessarily result in mycotoxin formation, which seems to depend on environmental conditions (Lacey and Magan, 1991).

Water available for biological and enzyme activity is measured as water activity (a_w), defined as the ratio of the vapour pressure of water over a substrate to that

of pure water at the same temperature and pressure, and equilibrium relative humidity (E.R.H.), which is the relative humidity (R.H.) of the atmosphere between the grains. Numerically these two measures are the same, although E.R.H. is expressed as a percentage and a_w as a decimal fraction in the range zero to one. The

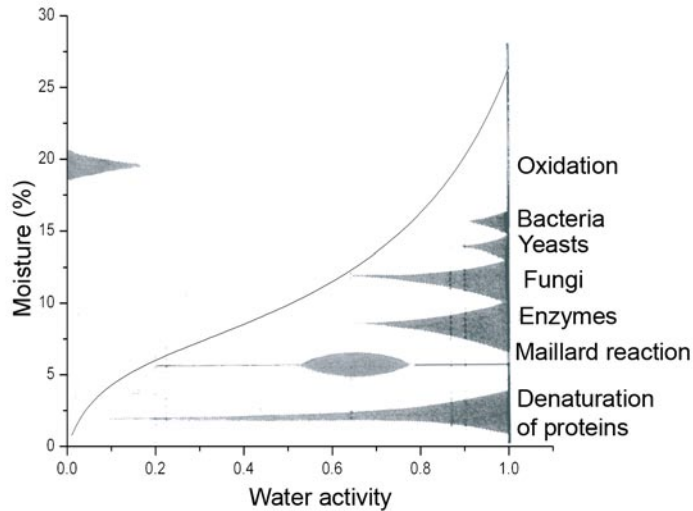


Figure 1. Sorption isotherm of oat groats showing risks during spoilage adapted from Multon (1988) and Gates and Talja (2004)

relationship of a_w to water content is frequently presented in the form of a sorption isotherm (Fig. 1).

In cereal science, the term moisture is frequently used interchangeably with water but, strictly speaking, moisture refers to any liquid that wets a material. The accurate determination of water content is challenging, and few laboratories use chemical analyses, such as the Karl Fischer method. Oven drying results in the evaporation of components other than water, and some water may still be retained by the sample. In this thesis, moisture is used to refer to these secondary methods for determining water content.

2.1.3. Drying and storage

Post-harvest handling and in particular drying and storage influence quality before the oats leave the farm. In Finland oats are typically harvested with a moisture content around 21 – 23% (Aaltonen et al., 1999). Unless they are dried, they are suscep-

tible to both sprouting and microbial spoilage. Under Canadian conditions, near ambient drying systems have proved a low cost technology, the only disadvantage being that drying occurs slowly (Jayas and White, 2003), which increases the risk of fungal and insect growth. On-farm driers are widespread in Finland, and these are often cold air or near-ambient driers. A survey found that over 50% of farms in the Southern Ostrobothnian region have their own drier (Holkko and Palva, 2003). Concerns over grain vitality and fire regulations have limited the air temperature in grain dryers to 80°C, but recent changes in the regulations, the need for energy saving and research findings will perhaps result in changes in drying procedures (Kemppainen and Kirkkari, 2002).

Drying involves heat and mass transfer. Initially as heat is transferred to the surface of the grain it evaporates liquid water from the surface. However, most grain drying occurs during the falling rate period, in which the internal resistance to water transport becomes important and the system becomes more complex involving capillary flow, diffusion and hydrodynamic flow (Parde et al., 2003). This has the effect of increasing the energy requirements for the process. Indeed globally, drying accounts for 10 – 15% of total industrial energy consumption (Kerckhof and Coumans, 2002) and grain drying requires between 1000 to 2000 kJ/kg of water (Bakker-Arema, 1986). Considerable savings can be achieved when the design of the dryer is optimised (Parde et al., 2003), which is of immense importance with the current concern over the climate change and instability in oil prices.

Optimisation of drying efficiency cannot be done at the expense of grain quality. Whilst high drying temperatures can reduce the bread making potential of wheat, due to changes in the gluten proteins. The role of proteins in oat quality is not clear, although due to the heat-treatments needed to stabilise oats thermal denaturation of oat protein during drying is unlikely to have any practical significance. Steep temperature and moisture gradients may also arise within the bulk, and even within the grain. In some cereals, notably those with hard, vitreous endosperm such as rice, these gradients cause internal stresses that result in cracking and fissuring (Kunze, 2001). Oat endosperm has a floury endosperm, so that cracks and fissures are not apparent. However, there is little or no published research into the effect of drying conditions on oat quality.

Incorrect storage conditions reduce the quality of grain. Pests, insects and microorganisms are a major threat to grain worldwide, especially in developing countries. If the moisture content of the grain is in excess of 14%, the risks are particularly high as the increased metabolic activity of the grain itself leads to a self-perpetuating increase in grain moisture (Pomeranz, 1982). Simple, rapid methods of measuring grain moisture are widely used by farmers, so the risk at well run storage facilities is minimal. One problem is, however, the effect of fluctuating temperature, which

leads to moisture migration. Large variations between temperature are observed between day and night, and also between seasons. As shown in Figure 2, water tends to move to migrate away from areas of higher temperature and condense

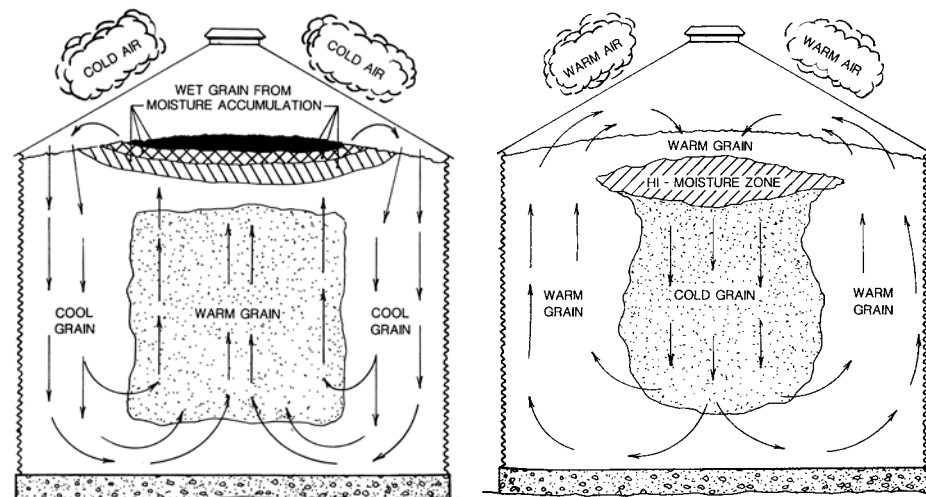


Figure 2. Moisture movement in stored grain as the result in temperature variations (from Foster and Tuite, 1982, with kind permission of the American Association of Cereal Chemists).

in cooler regions. Thus, “uniformity of moisture in grain bulks is a concept, not a fact” (Christensen et al., 1982). Aeration or regular turning helps to maintain a uniform temperature, equalise moisture and remove excess dryer heat (Foster and Tuite, 1982).

Only few studies report on grain temperatures in storage, and many of these studies are not relevant to the climatic conditions in Finland. One study undertaken in Winnipeg, Canada showed that size, shape, colour, bin construction material, orientation of rectangular bins and turning of the bin influenced the temperature in a grain bulk (Jayas et al., 1994). Minimum temperatures at the centre of the bin were as low as -14°C for small bins (Jayas et al., 1994), but in other cases the grain can remain warm ($15 - 20^{\circ}\text{C}$) throughout the Canadian winter (Jayas and White, 2003). The cold, dry conditions typical of Finnish winters could be more fully exploited. Prolonged freezing can kill insects and reduce the need for fumigation. These conditions are also not favourable to storage fungi.

Storage in itself also affects the quality of grain, and improvements to bread making quality due to maturation are well-documented for wheat (Pomeranz, 1982), and appears to be related to an increase in the amount of insoluble glutenin in the

flour (Gras and Riordan, 1998). Storage temperature was shown to greatly influence glutenin solubility and bread volume and crumb softness (Gras and Riordan, 1998). It has also been shown that the viscosity of unground wheat soluble fibre extract decreased during storage and that the decrease was greater at low storage temperatures, but viscosity increased if the wheat was ground before storage (George and McCracken, 2003). The effect of storage on the quality of oats does not appear to be documented.

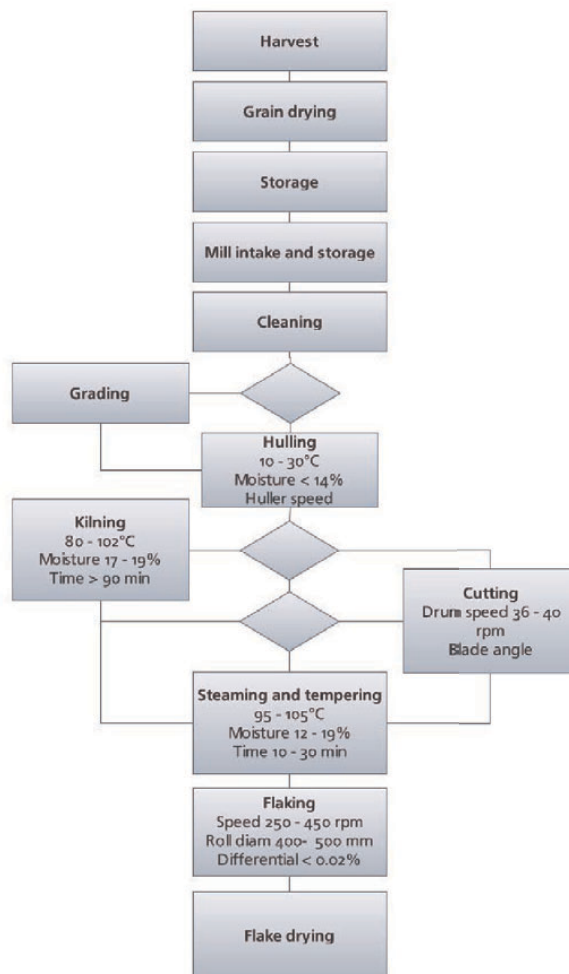


Figure 3. Outline of the oat flaking process.

2.2. Mill processing

The oat flaking process consists of a series of unit operations that are shown in Figure 3. As with any industrial process, mills will adapt this general flow to suit their needs.

2.2.1. Intake and cleaning

Mill processing starts with the arrival of oats from the farm or storage facility. The miller only accepts oats that will yield flakes of satisfactory quality, and will attempt to maximise profits by estimating the potential yield and looking at the price of the oats and any possible added value obtainable (e.g. “organic”). It is also through the use of contracts, offering financial incentives for quality, that the mill is able to influence the decisions taken by the farmer.

The main criteria used to select oats remain much the same as those given by Hutchinson in 1953 : the oats must appear wholesome and clean, must be free from extraneous material, with large and light coloured oats that give a high yield being preferred. At that time a groat yield of 73% was considered fair and small oats, less than 2 mm wide and weighing less than 16 mg were considered ill-suited for mill processing. The minimum test weight accepted by millers was 47.5 kg/hl. Hutchinson also suggested the thousand grain weight as a measure of groat content, discounting the value of test weight. A more recent report (Galbraith, 2004) gave the quality requirements of the Canadian milling company Can-Oats as:

- Test weight 50 kg/hl
- Wheat, barley and wild oats max. 2%
- Heated max. 2%
- Ergot, sclerotia and fire burnt zero tolerance
- Total damaged and foreign material max. 4%
- Dehulled max. 6 %
- Thin oats (<1.98 mm) max. 10%
- Moisture max. 13%

The Codex Alimentarius Commission, a group set up by the Food and Agriculture Organisation (FAO) and World Health Organisation (WHO) with the task of protecting consumer health and promoting fair trade practices issued a standard (201-1995) for food-grade oats. The emphasis was on safety, a maximum moisture content of 14% is specified and various toxic and noxious contaminants are listed with specific limits. They also give some recommendations for technological quality, specifying a minimum test weight (46 kg/hl) as well as maximum limits for: hull-

Table 1.Quality of Finnish oats 2001 – 2005

Harvest year	Test weight kg/hl	Protein %, d.b	Thin grain, <2mm, %	Hull content %
2001	56.2	13.4	7.6	—
2002	54.4	13.8	8.5	—
2003	54.9	14.2	10.3	—
2004	55.1	12.9	6.2	—
2005	55.1	12.8	8.4	23.1

Source: Finnish Food Safety Agency, 2006

less and broken kernels (5%), edible grains other than oats (3%), damaged (mould, heat, sprouted etc.) kernels (3%), wild oats (0.2%), insect bored kernels (0.5%) and blemished (due to climatic factors) grains (limit undecided). Ganssmann and Vorwerck (1995) recommended a minimum test weight of 53 kg/hl, a thousand grain weight of at least 27 g (dry basis) and set maxima for moisture (15%), husk content (26%), double oats (0.8%), foreign material (1%) and foreign grain (1%). They also included evaluation of the appearance and flavour and limit thin grains (<2 mm) to 10%. Annual harvest statistics show that Finnish oats generally exceed these requirements (Table 1).

When a lot is accepted, it is transferred to a silo at the mill. Since 2005, European regulations (“Regulation (EC) No 178/2002,” 2002) have placed the responsibility for safety on food business operators and have demanded “one step back-one step forward” traceability with the aim of protecting consumers, especially when a product is faulty . In practice, this has meant that food producers have to maintain documentary evidence that these obligations have been fulfilled. With a small amount of extra investment it is generally possible to also use this documentation to benefit the company activities. Statistical analysis of intake data, for example, could be used in conjunction with product release data to identify key quality factors in oats and identify suppliers of these superior oats. However, most of this information is unlikely to be made publicly available.

The oats are then cleaned, mainly on the basis of physical properties of the grain. Sieves are used to remove contaminants on the basis of size. Differences in density are exploited in aspiration and dry-stoning. Disk and drum separators use carefully designed pockets to lift particular contaminants out of the bulk on the basis of their shape. Magnets are used to remove ferrous metals at each stage of processing (Ganssmann and Vorwerck, 1995). In recent years there has been considerable interest in machine vision, and various researchers have studied the possibility of cleaning and grading cereals according to their shape, size and colour (Majumdar and Jayas, 2000). One advantage of an optical system is that it could identify sprout-

ed and mouldy grains, which conventional systems cannot. There are commercial optical sorting systems available (for example from Bühler), although currently these are not widely used in oat mills.

2.2.2. Impact hulling

Hulling efficiency is central to the economic success of the mill (Ganssmann and Vorwerck, 1995; Webster, 2002). As well as representing a source of material loss through breakage, consumers find the presence of hulls unacceptable and will soon reject brands with high hull contents. In Japan, a country unfamiliar with oats, some companies set the limit as low as 3.5 hull pieces per kilogram (Erkki Pöytäniemi, personal communication). Furthermore, the presence of broken groats increases the susceptibility to storage pests, such as the flat grain beetle (*Cryptolestes pusillus*) and the sawtooth grain beetle (*Oryzaephilus surinamensis*) (Throne et al., 2003) .

Impact hulling is the most widely used industrial method for removing the tough, inedible hulls that cover the groat (Ganssmann and Vorwerck, 1995). Oats are fed through a hollow shaft of the machine (Fig. 4) to the centre of a rotor, that is equipped with vanes. The oats are thrown against an impact ring made of rubber, steel, plastic or composite material, that is attached to the housing of the machine (Youngs et al., 1982; Ganssmann and Vorwerck, 1995). The speed of the rotor is adjusted so as to maximise the yield. If an unsuitable, or poorly adjusted, aspirator is used, the separation of groats from hulls will be poor, which is especially a problem with experimental systems (Doehlert and McMullen, 2001). Yield is thus a com-

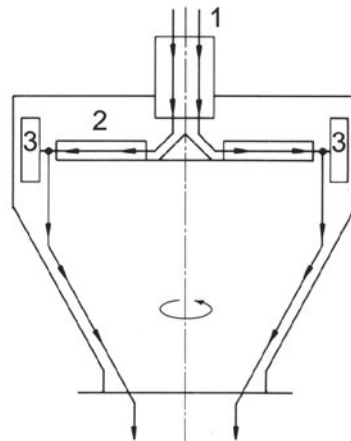


Figure 4. Schematic representation of an impact huller showing hollow shaft (1), rotor (2) and impact ring (3). From (Ganssmann and Vorwerck, 1995), with kind permission of Springer Science and Business Media.

promise between hulling efficiency and groat breakage (Doehlert and McMullen, 2001; Peltonen-Sainio et al., 2004b), and is also dependent on the efficiency of the separation of groats and hulls.

In the hulling operation, the grain hits the impact ring head-on and is rapidly decelerated, resulting in a force proportional to the mass of the grain. The force is concentrated in the area of the grain that is in contact with the ring. High speed imaging of individual kernels impacting a steel surface, showed that the groat was released from the hulls almost instantly on impact, and the hull broke into a number of pieces (Gates et al., 2001).

Some oats retain their hulls, and these are sent back to the huller. They may be weakened by the impact, even if this is not visible. This impact damage primarily occurs at the proximal (germ) end of heavier kernels (Symons and Fulcher, 1988b). Breakage will largely depend on the groat mass and rotor speed (that together largely determine the impact force) and the mechanical properties of the groat and the impact ring.

Factors affecting hullability

Differences in the structure of the groat may explain much of the variation in hullability seen between cultivars and the location in which they were grown. The size and shape of oat kernels have been studied in relation to hullability (Symons and Fulcher, 1988a; Browne et al., 2002; Doehlert et al., 2002; Doehlert et al., 2004), using various methods to characterise the size and to determine the groat yield. This makes comparisons between the studies difficult. A characteristic of oats is that they are multi-floreted and the spikelet may contain between one and three kernels. This results in a multi-modal distribution of length (Symons and Fulcher, 1988a; Doehlert et al., 2004), but the width of the kernel showed a uni-modal distribution (Doehlert et al., 2004). Differences in the hullability of primary, secondary and tertiary grains have also been demonstrated (Browne et al., 2002).

Grading on the basis of size improves groat yield (Youngs et al., 1982; Ganssmann and Vorwerck, 1995). Size may be characterised either as weight, or as the dimensions of the grain or the groat. The dimensions of the grain can be determined by either sieving, which is more representative of industrial practices, or by image analysis, which provides more information. Doehlert et al. (1999) studied the relationships among hull breakage, hulls remaining after dehulling and the size of the kernel and the groat. They found weak ($R^2 < 0.3$) correlations between oat width, oat image area and groat breakage during impact hulling. Oat length and its coefficient of variation correlated weakly with hulls remaining. They concluded that test weight and size uniformity determined by image analysis were the kernel characteristics that correlated most highly with groat yield, however, the correlation were still rather weak ($r < 0.7$).

Hutchinson (1951) dismissed test weight as “a rough index of the amount of millable grain present in the average sample”, and suggested that thousand grain weight was a better measure. Ganssmann and Vorwerck (1995) reported a strong correlation ($r = 0.91$) between percentage of husk and milling yield. Symons and Fulcher (1988b) showed that milling yield could be correlated with kernel (groat with hull) weight. However, the determination of hull weight is impractical and a method is needed that would enable millers to predict mill yield at intake. A Finnish study showed a highly significant correlation between groat yield and test weight ($R^2 = 0.98$) for a single cultivar (Salo) grown for official variety trials over 5 years (Peltonen-Sainio et al., 2004b). These contradictory findings reflect the difficulties in controlling all the parameters involved in hulling.

The mechanical properties of oat have been reviewed earlier (Gates and Dobraszczyk, 2004). The mechanical properties of oats have also been shown to influence hullability. Doehlert and McMullen (2000) used the Perten Single Kernel Characterisation System to determine the hardness index, and found a weak, but significant negative correlation between hardness and groat breakage. Engelson and Fulcher (2002a) compressed groats along the major axis with a Texture Analyser and calculated the apparent stress, strain, stiffness and toughness. They found a complex relationship of impact damage with moisture squared, starch content and the cube of the ratio of apparent toughness to apparent stiffness. The authors point out that results were based on a small sample and may not be generally applicable.

Water affects the mechanical properties of the groats (and the hulls), generally acting as a plasticiser, softening most biological materials, including cereals. Some recent studies have suggested that at a certain level water can also have a strengthening, anti-plasticising effect in starchy, cereal-based materials (Harris and Peleg, 1996; Gondek and Lewicki, 2006). It is therefore not surprising that many studies have shown that moisture content influences groat yield. Ganssmann and Vorwerck (1995) reported that hulling efficiency was higher in dry oats. In reality the situation is more complex, as a minima for hulling efficiency at around 15 – 20% moisture has been shown (Doehlert and McMullen, 2001; Peltonen-Sainio et al., 2004b). The distribution of water may also be a factor, as in both these studies the oats were dampened and tempered overnight. In normal processing, the oats would be dried, not dampened. However, there do not appear to be any studies on how wetting and drying affect water distribution or processing.

Other factors such as sprouting (Doehlert and McMullen, 2003) and crown rust infection (Doehlert and McMullen, 2000) increase groat breakage. This is probably due to the breakdown of cell walls, and this is further confirmed by a negative correlation between breakage and beta-glucan content (Doehlert and McMullen, 2000) and the role of beta-glucan in toughening of the groat (Engelson and Fulcher, 2002a). Examination of the oat microstructure has also revealed that the distribution of beta-glucan can differ between cultivars, and that in the cultivar with the

higher milling energy it is concentrated in the sub-aleurone layer (Salmenkallio-Marttila et al., 2004). In that study there were no differences in the milling energy after germination and the largest changes were observed in the crushed cell layer below the scutellum. This was in keeping with the conclusion of Engleson and Fulcher (2002a), that the pericarp is involved in protecting the groat during hulling.

Other hulling systems

Whilst the majority of modern oat mills use impact hullers, two other systems are worth considering briefly: compressed air and stone hullers. Compressed air hullers are used in laboratories, and sometimes at mill intake, to estimate groat yield and to obtain samples. These systems use air to accelerate the oats, which are recycled in the system for a known period of time. Air pressure can be varied to control impact speed, and by decreasing vent opening it is possible to change the strength of the aspiration (Doehlert et al., 1999).

Before the advent of impact hulling, the stone hulling system was used industrially and is described in length by Ganssmann and Vorwerck (1995). The system consisted of two horizontal, cast iron disks (the “stones”) arranged one above the other, with one of the disks being covered with emery. The upper disk was stationary and had an opening through which the oats are fed. The lower disk rotated rapidly. The distance between the stones was adjusted to the grain length. The oat was caught from above and below by its tips and the motion of the stone freed the groat. To achieve this, the groats must be very dry (8 – 10% moisture), and this is the origin of the use of the kilning system.

2.2.3. Kilning

A hydrothermal treatment, known as kilning, is often used because the high lipid content and active enzyme system of oats (Galliard, 1983) makes them susceptible to rancidity. The process involves the direct addition of steam followed by treatment in a radiator kiln, as shown in Figure 5. The primary aim of the kilning process is to inactivate lipid hydrolysing enzymes. According to Ganssmann and Vorwerck (1995), the process also reduces microbial loads on the groat surface and is involved in flavour formation.

In Germany, typically the retention time in the kiln is about 90 – 120 minutes (Ganssmann and Vorwerck, 1995). An Australian study gives typical conditions as “steaming for 9 minutes, kilning at 100°C for 45 minutes and 65°C for 15 minutes”, the groats then being cooled to room temperature (Zhou et al., 2000b). A Finnish process is described as steaming for 2 – 3 minutes at 100°C, which increases the

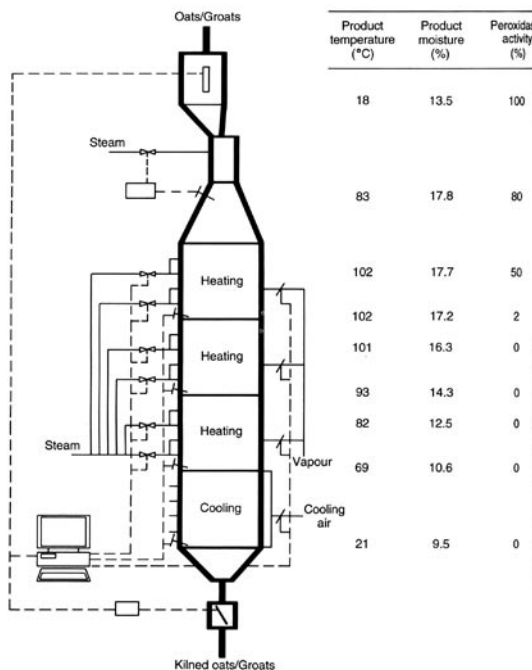


Figure 5. Schematic representation of kilning showing a typical temperature-moisture profile. From Ganssmann and Vorwerck, 1995. With kind permission of Springer Science and Business Media.

moisture content of the groats from 12 – 13% to 16 – 17%, followed by treatment at >95°C for over 70 minutes, the groats are then dried to 13% moisture over >30 minutes (Salovaara, 1993). These examples reflect differences in processing conditions used, and probably also in the ways in which they are described. In industrial processes, a feedback loop is used to control steam addition. Thus the transit time in the steaming section does not translate directly into steaming time, as the steam flow is intermittent.

To describe the intensity of a heat treatment, for example when considering lipase inactivation, the temperature, duration of the process and also the moisture content of the oat need to be considered. In the dynamic conditions found in kilning, it is difficult to compare results from different experimental systems, since the rate of heating and cooling together with countless other interdependent factors. The total energy added may be a suitable starting point, but this is difficult to estimate in a unsteady state system. Furthermore, the inactivation of enzymes is dependent on the amount of free water and how it is distributed.

Dry heating is not generally an effective method of reducing lipase activity, compared with steaming which effectively inactivated lipase. Although the main inter-

est is in enzymes that cause rancidity, most mills use peroxidase as an indicator of storage stability, because simpler and quicker analytical procedures are available for peroxidase. It is not clear from the literature how lipase inactivation compares with that of peroxidase. Vorwerck (1988) showed data indicating that lipase is more heat stable than peroxidase, whereas Ekstrand et al. (1992) showed that lipase was inactivated before peroxidase.

The moisture content during oat processing remains below 25%, and there have

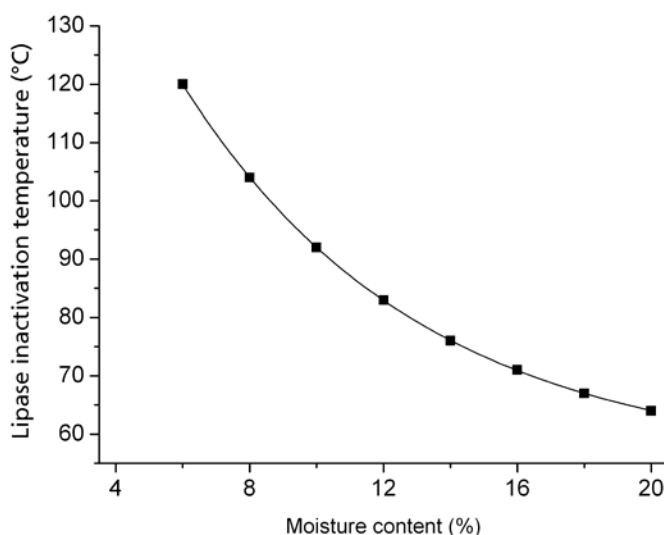


Figure 6. Dependence of lipase inactivation temperature on moisture content. Data from Hutchinson et al. (1951).

been few studies of enzyme inactivation under such dry conditions. The effect of moisture content on the temperature required to achieve a 97 – 98% reduction in lipase activity during a one hour heat-treatment has been shown (Hutchinson et al., 1951) and is shown in Figure 6. Residual peroxidase activity was also observed after 45 minutes kilning (Zhou et al., 1999). In one study, the free fatty acid content of samples that underwent dry heating and steaming was far lower after 16 weeks storage than those samples that were only steamed (Ekstrand et al., 1993), even though lipase activity was detected in the dry heated samples.

The majority of the lipase activity is found in the germ and in the aleurone layer (Sahasrabudhe, 1982; Ekstrand et al., 1992), with higher activity was found in immature oats (Sahasrabudhe, 1982). Since these are surface layers, a short heat treatment should suffice. However, low levels of lipase activity are found in the en-

dosperm and may affect product stability (Lehtinen et al., 2003). Residual activity may also be due to variations within the bulk, and the low levels of enzyme activity found may be due to a small number of individual groats passing through the kilning process with an intact enzyme system.

As well as enzymes, other proteins are denatured by the steam treatment of oats. The solubility of the proteins decreases (Oomah, 1987), which may have implications on the technological functionality of these proteins. The electrophoretic pattern of the avenin fraction was not, however, affected by kilning or flaking (Lookhart et al., 1986) and thus varietal identification should be possible for flakes (Jussila et al., 1992). Electrophoresis could thus be a useful tool to identify cultivars that result in flakes with differing textural characteristics.

The sensory properties are affected by kilning (Molteberg et al., 1996; Sides et al., 2001). Trained panellists were able to differentiate between the taste of ground raw groats, kilned groats and flakes; the kilned groats had the strongest overall aroma and flavour (Sides et al., 2001). Steaming with the hulls gave the greatest flavour intensity, but was also associated with bitterness and rancidity (Molteberg et al., 1996). These quality factors will be discussed later.

2.2.4. Steam tempering and flaking

Steam is added to the oat groats prior to flaking, to increase the moisture and temperature, thus plasticizing the groat. Steam is an efficient and highly controllable

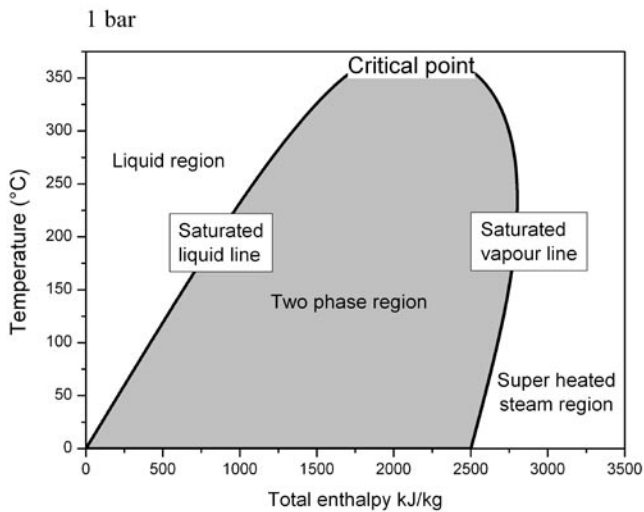


Figure 7. Temperature enthalpy phase diagram for steam at 1 bar. Data from <http://webbook.nist.gov/chemistry/fluid/>

medium for distributing energy. A major advantage to the food industry is that steam is inherently non-toxic and hygienic. Industrial steam is generally under pressure, which enables it to be conveyed without the need for pumps and also reduces both the volume of the steam and, consequently, the diameter of the pipes needed to transport an equivalent amount of energy. The boiling point of water also increases with pressure, and the relationship of these properties is expressed in steam tables or graphically as a phase diagram (Fig. 7). After crossing the saturated liquid line, steam in the two phase region increases in dryness fraction as the enthalpy increases, until at the saturated vapour line it is 100% dry. Any further addition of energy results in superheated steam. Superheated steam can be used for grain drying, and offers the advantages of reducing the mycotoxin deoxynivalenol (DON) and bacterial spore loads, although the high capital cost of the equipment is a drawback (Cenkowski et al., 2006).

Steam treatments are complex as they involve the addition of considerable amounts of energy at constant or nearly constant temperature. This is the result of the phase change involved in condensation (McCabe and Smith, 1967). Heat transfer occurs primarily through convection, which thermodynamically is a flux of enthalpy rather than a form of heat flow (McCabe and Smith, 1967). Since convection describes the macroscopic and diffusional forces acting on particles, it is closely associated with fluid mechanics. Conduction and radiation are also involved in the redistribution of heat in the grain bulk and to the walls of the steamer.

Structural features of the oat groat in relation to flaking

Oats are traditionally flaked. One reason for this seems to be the natural propensity for oat groats to form flakes. The majority of the groat is occupied by the endosperm, which is composed mainly of starch, followed by proteins and lipids (Fulcher, 1986; White, 1995). The starch is in the form of polyhedral granules about 3 – 10 μm in diameter, these form compound around 20 – 150 μm in diameter (Fulcher, 1986; Hosney, 1998). Oat proteins are also deposited in discrete bodies about 0.14 – 1.33 μm in diameter. Unlike the protein bodies of the aleurone layer, these bodies in the endosperm are almost pure protein and do not contain phytic acid (Donhowe and Peterson, 1983). In oats, the cell walls of the endosperm remain largely intact (Fulcher, 1986).

The mechanical properties of oat groats have been reviewed in more detail previously (Gates and Dobraszczyk, 2004), but some key points are discussed here. The absence of a continuous protein matrix around the starch granules, which is typical of wheat (Hosney, 1998), results in a soft groat that does not fracture as readily. A brittle-ductile transition was not detected in large deformation compression, at low moisture content (9 – 10%) the groats failed by plastic compression and buckling, but at over 12% moisture they burst open near the mid-point (Engleson and Fulcher, 2002b). A glass transition temperature for oats has not been published,

although it has been reported for many other seeds (Williams, 1994; Sun, 1997). The most common method for studying the glass transition is differential scanning calorimetry (DSC), however, for products containing starch DSC is often not sensitive enough to detect the glass transition (Champion et al, 2000). However, the sharp change in the rheological properties associated with the glass transition can be detected by mechanical spectroscopic methods (Champion et al, 2000), such as dynamic mechanical analysis DMA. This method involves applying a small sinusoidal perturbation to the system, from the response it is possible to determine the absorption of energy (loss modulus, E''), as well as the elastic response (storage modulus, E'). The peak of $\tan \delta$ ($\tan \delta = E''/E'$) or the maximum of E'' are often termed the alpha relaxation. Whilst this relaxation is related to the glass transition they are not fully equivalent due to the different physical nature of the stresses imposed, these are thermal in DSC and mechanical in DMA (Champion et al, 2000).

The determination of the glass transition, a phenomenon occurring at the macromolecular level, is made in the linear viscoelastic region. This is because non-linear behaviour such as plastic deformation or fracture is difficult to model. However, it is this non-linear behaviour that dominates in processes such as flaking. The ductile behaviour of the oats during compression observed by Engleson and Fulcher (2002b) may be the result of the granules sliding past each other, in the absence of a continuous protein matrix. The role of the cell walls in determining the mechanical properties is not clear, but there are reports linking cell wall components, such as β -glucan and phenolics, to groat strength (Doehlert and McMullen, 2000; Engleson and Fulcher, 2002a). These components are also most abundant in the bran layer, which also has a role in flake integrity (McDonough et al., 1997).

Steam tempering and physical changes in the groat

The primary function of the steaming associated with flaking is to reduce breakage and to yield stronger flakes (Ganssmann and Vorwerck, 1995). The addition of heat and moisture softens the groat, making it more ductile and less susceptible to brittle fracture (Dobraszczyk and Vincent, 1999). This is commonly understood in terms of the glass transition, which describes the change in state of amorphous polymers resulting from changes in plasticization and temperature (Roos, 1995). Flake strengthening occurs when the adhesion between the structural elements of the flake are increased. However, the exact mechanism for this strengthening effect of steaming has received little attention in the literature. Studies on sorghum have shown that during steam tempering and flaking, starch leached from the granules and formed a glue-like continuous phase, which held the starch granules together and bonded the ruptured bran layer to the surface of the flake (McDonough et al., 1997).

Heat treatment significantly affected the pasting characteristics of oats. During flaking the maximum moisture content of the groats is less than 20% (Ganssmann and

Vorwerck, 1995), which limits the gelatinisation of starch (Oomah, 1987; Zhou et al., 2000b). However, the compound starch granules have been observed to fracture into their individual granules during kilning and flaking (Lookhart et al., 1986). An increase in the pasting temperature and peak viscosities of oat starch were also observed when it was treated at 50°C (Hoover and Vasanthan, 1994). Processing, involving kilning (100°C for 45 min.) and steam flaking, increased the viscosity after pasting, although this was attributed to inactivation of enzymes (Zhou et al., 1999). The same process was later shown to cause a decrease in the temperature and enthalpy of gelatinisation, as determined by differential scanning calorimetry (DSC) (Oomah, 1987; Zhou et al., 2000b), confirming an earlier study (Oomah, 1987). However, there is evidence to suggest that this is not exclusively the result of enzyme inactivation, as roasting for 2 hours at 130°C resulted in a decrease in paste viscosity (Zhang et al., 1997). Processing also increased the temperature of the second peak on the thermogram by about 2°C. This peak, around 95°C, corresponded to the dissociation of the amylose-lipid complex (Oomah, 1987; Zhou et al., 2000b).

Flaking

The flaking of cereals has not been the subject of much scientific research, apart from a recent series of publications by Levine and others (Levine, 1993; Levine and Levine, 1997; Levine et al., 2002; Levine et al., 2003; Levine et al., 2004a; Levine et al., 2004b), which investigated the physics of the flaking, using extruded cereal pellets and a polymeric dough as model materials. During flaking the groat passes between two rolls that are typically 400 – 500 mm in diameter (Ganssmann and Vorwerck, 1995). Flaking is similar to other unit operations, such as calendaring used in the paper (Rodal, 1993) and plastics industries (Ray and Shenoy, 1985) and the rolling of metals (Dieter, 1986). These are generally considered as steady state processes, whereas oat flaking is an unsteady state operation since the oat groats pass through the nip individually. Comparisons can, however, be made between the problems that arise in flaking and those that occur in other industries.

In metal rolling, it has been observed that the thickness of a sheet exiting the rollers is always greater than the roll gap. This is a result of severe elastic deformation of the material and is known as *mill spring*. Mill spring sets a minimum thickness for the sheet, since the pressure required to hold the rolls in position is limited. This limiting thickness is also related to roll radius, with larger rolls being capable of producing thinner sheets (Dieter, 1986). This has implications on laboratory scale equipment. Sideways spreading results in defects in rolling (Dieter, 1986), and ragged edges have also been observed to increase in model flakes as the size of the pellet increased (Levine and Levine, 1997). Spreading related both theoretically and experimentally with the reduction ratio (Levine et al., 2002), thus small or cut groats would spread less and consequently have less flawed edges.

If a single pellet is considered, the flaking process can be envisaged as consisting of three phases: entry, filled nip and depletion stages (Levine and Levine, 1997). During the entry stage, the pellet enters the nip and the leading edge is deformed and spread sideways, as the pressures and shear forces exerted on the pellet increase rapidly. At the filled stage, the pressures and shear forces are maximal. Then as the flake exits the rolls, the undeformed pellet material begins to deplete. As this occurs, the pressures and shear forces exerted on the material will decline, reaching zero when the flake completely exits the rolls. A pressure field exists within the contact region between the rolls, peak pressure is observed at some point behind the leading edge, and the pressure drops off again towards the trailing edge of the pellet. It is obvious that material will attempt to flow away from regions of high pressure. Observational evidence, from polymeric dough pellets, confirmed that elongation of the flake increased with decreasing roll diameter and that the trailing edge of the pellet was always thinner than the rest of the flake. The shape of the pellet and roll gap had complex effects (Levine and Levine, 1997). The speed of the flaking rolls and, for materials that are not elastic, the rheological properties of the pellet had no effect on the shape of the flakes (Levine and Levine, 1997; Levine et al., 2003). Oat groats, however, have a strong elastic component (Gates and Talja, 2004).

The high shear and work inputs of flaking modify the structure of the groat, disrupting cell walls, starch granules and protein bodies (Lookhart et al., 1986). Furthermore, the physicochemical properties of macromolecules, such as starch and proteins, can be modified. Even extruded pellets, which were heated and subjected to considerable shear, showed increasing Rapid visco analyser (RVA) peak viscosity with increasing flaking work input (Levine et al., 2004).

2.3. Quality and its relationship to end uses of oat flakes

2.3.1. Physical properties

Bulk density is used by the miller to control the flaking process, as this relates to many quality parameters. As well as affecting pack filling, bulk density measures flake thickness. The principle method of controlling flake thickness is by adjusting the roll gap. The size of the flakes, or granulation, is determined by the groat size and flake thickness. Flake pieces passing through a 2 mm sieve are an indication of poor flake integrity (Rhymer et al., 2005). Flake breakage is a problem because it results in an inhomogeneous product that causes difficulties in industrial processes and is unattractive to consumers. Certain cultivars produce flakes that are more resistant to breakage (Rhymer et al., 2005) and the smaller flakes obtained from cut groats are also more resistant. In addition, as has been noted earlier, steaming

and tempering conditions during flaking also influence flake breakage. Breakage is closely linked to the texture of the flake.

The textural properties of dry, cereal foods are closely related to their moisture content and this has been related to the glass transition (Peleg, 1994; Sapru and Labuza, 1996). Flake texture is mainly relevant in products where the flakes are eaten without cooking, such as muesli. In a multi-component system, such as muesli, water migrates between the components as the water activity of the system attempts to reach equilibrium (Sapru and Labuza, 1996). In formulating such multicomponent foods, it is essential to determine the sorption isotherms of all the components, as the stability of the product as well as the texture will depend on the distribution of water within the food.

2.3.2. Water absorption

Oat flakes are commonly mixed with cold water or milk, for example during manufacture of biscuits or snack bars. In these industrial processes, the influence of water absorption on the consistency of batters and doughs is important, as variations in consistency can affect the spreading of biscuits. This has consequences on pack weight and may present problems during packaging.

If oat flakes are added to a large amount of water, it is reasonable to assume that the surface will become saturated with water almost instantly and will remain at near saturation until equilibrium is reached. The rate controlling step in water absorption is generally assumed to be diffusion (Hsu, 1984; Machado and Oliveira, 1998). Initially water uptake is rapid, but the rate decreases as equilibrium is approached. The presence of a barrier, such as sugar frosting, retarded water uptake (Sacchetti et al., 2003). Another study demonstrated that non-diffusion mechanisms dominated (Machado and Oliveira, 1998). Pores and other structural discontinuities allowed water to progress ahead of the diffusion front, whereas fat impeded its movement. The textural changes in oat flakes during water uptake are important in ready-to-eat breakfast cereals, such as muesli.

2.3.3. Stability and flavour

Flavour is also considered an important quality factor and has been extensively studied (Haydanek and McGorin, 1986). Of particular relevance is the absence of the rancid, soapy and bitter flavours associated with lipid degradation and oxidation (Hutchinson, 1953) and the presence of a toasted odour and flavour (Lapveteläinen and Rannikko, 2000). The bitter and astringent tastes are due to hydrolysis reactions, whereas the rancid flavours arise from separate oxidation reactions and it has been noted that efforts to prevent one reaction pathway often promote the other

(Lehtinen and Laakso, 2004). In particular, excessive heat treatment to inactivate lipase has been shown to promote the oxidation of polar lipids (Lehtinen et al., 2003). Oat lipases are unusual among enzymes, in that they are most active in the relatively dry conditions found in cereal grains (Galliard, 1983). If excessive fatty acid is produced, this can overwhelm the antioxidant capacity of the grain (Peterson, 2001).

Phenolic compounds are also responsible for the flavour, and compounds such as coniferyl alcohol, *p*-hydroxybenzaldehyde, vanillin, vanillic acid, *p*-coumaric acid and ferulic acid were all associated with rancidity, bitterness or a lower level of fresh odour in oat flakes (Molteberg et al., 1996). Many of these compounds have antioxidant effects, and some such as vanillin and *p*-hydroxybenzaldehyde have pleasant aromas, thus their unexpected association with off-flavours was explained in terms of breakdown products (Molteberg et al., 1996). Volatile compounds affect the sensory properties, particularly aroma, of the flakes, but they also contribute to the flavour of cooked oatmeal porridge (Zhou et al., 2000a). Hexanal concentration, which is commonly used to monitor lipid oxidation, did not relate closely to free fatty acid content. In a sample that had undergone dry heat treatment, hexanal increased for 30 weeks and then declined sharply (Ekstrand et al., 1993).

The heat treatments used during flaking are generally sufficient to inactivate the lipolytic enzymes in the oats and if the flakes are stored in cool (<20°C), dry (R.H. < 65%) conditions they should remain in good condition for 1 – 2 years (Ganssmann and Vorwerck, 1995). Often a peroxidase test is used to verify the absence of enzyme activity. Heat processing (kilning) has been shown to influence the flavour of oat porridge (Molteberg et al., 1996; Zhou et al., 2000a; Sides et al., 2001), as has oat cultivar (Molteberg et al., 1996; Zhou et al., 2000a). To ensure a good, fresh taste, consideration should also be given to packaging solutions since the enzymes are less active when the moisture content of the flakes is low (Drapon, 1985). However, at very low water activities (<0.25) there is an increase in the susceptibility of the lipids to oxidation (Multon, 1988; Jensen and Risbo, 2007). Jensen and Risbo (2007) showed that there was a minimum for oxidation rate, measured in terms of hexanal, of oat flakes from 23% to 43% R.H. They also showed that water decreased the stability of free radicals. According to that study the monolayer value according to the Brunauer–Emmett–Teller (BET) and Guggenheim–Anderson–de Boer (GAB) isotherm models did not correspond to the maximum oxidative stability. Removal of oxygen could also help reduce oxidation.

2.3.4. Pasting and the quality of cooked oatmeal

Apart from muesli, oat flakes are seldom eaten raw. Thus the behaviour during cooking is relevant to quality. As was mentioned earlier, oats contain a considerable

amount of soluble fibre, and this together with the heat treatments during processing has a major influence on the pasting properties. The onset of gelatinisation of native oat flour was found to vary between 59.5 – 62.2°C and to the gelatinisation peak temperature was at 64.4 – 67.1°C (Colleoni-Sirghie et al., 2004). Pasting is the increase in viscosity during cooking and peak viscosity was not observed until the slurry was cooked for some time at 95°C (Colleoni-Sirghie et al., 2004). Onset of pasting for freshly ground, native flour was reported as 68.5 – 84.8°C (Zhou et al., 1999). Kilning and the steam tempering associated with flaking stabilised the pasting properties during storage as well as prolonging the time to reach peak viscosity and increasing peak viscosity (Zhou et al., 1999).

Viscosity, evaluated as “the force required to stir porridge with a spoon” was one of the main sensory characteristics of porridge (Lapveteläinen and Rannikko, 2000). “Slipperiness” and “adhesion to the spoon” were the two other rheological properties included in the profile, which also included colour, odour and flavour attributes of the porridge. Particles that remained after cooking were also included in the sensory profile in various forms, namely: “average size of swollen flake particles”, “uniformity of the mass” and “coarseness” (Lapveteläinen and Rannikko, 2000). These properties could be expected to relate to the hydration and pasting properties of the flakes and to cooking method. This was confirmed in their later studies, which found that starch content and flake thickness related to slipperiness, uniformity, adherence to the spoon and also to the maximum viscosity determined in a Brabender Amylograph (Lapveteläinen et al., 2001). Significant variation between cultivars and harvest years was found (Lapveteläinen and Rannikko, 2000; Lapveteläinen et al., 2001). A similar Canadian study, in which the texture was determined instrumentally, also found that growing location was significant (Rhymer et al., 2005).

Lapveteläinen and Rannikko (2000) described the difficulties of trying to standardise the cooking, sample presentation and evaluation procedures, since the properties change with time and temperature. Cooking porridge in an RVA and using an instrumental method, such as texture profile analysis (TPA), allows for tight control of both cooking and evaluation, and this procedure was used by Rhymer et al. (2005). The cooking protocol needs to be considered, bearing the final process in mind. Since cooking procedure had a major effect on the characteristics of the sample. When the flakes were added to cold water, the sample was lighter in colour, more uniform, less slippery, less coarse and the swollen flake particles were smaller than when the flakes were added to boiling water (Lapveteläinen and Rannikko, 2000). Consumer practices may vary from country to country, and industrial processes vary considerably.

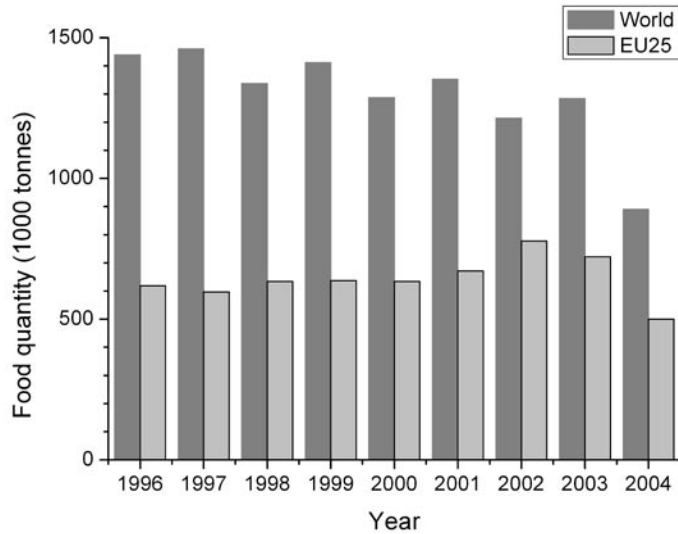


Figure 8. Oat consumption data for 1996 – 2004 (source (FAOSTAT, 2006)).

2.4. End-uses of oats

Quality is dependent on end-use, and porridge remains the main food use of oats in both Europe and the USA, followed by cold breakfast cereals (Pullinen, 1998). Various types of flakes are available to consumers, from thick flakes prepared from whole groats to small, thin flakes prepared from cut groats that receive special steam treatments to render them instant (Ranhotra and Gelroth, 1995). Industrially produced snacks, such as biscuits and bars also represent a major use for oat flakes. In the European Union (EU) there was considerable growth in this sector in the 1990s (Pullinen, 1998). According to that study oat usage was predicted to increase, but this trend was not observed from food consumption data (Fig. 8).

To assure the long term acceptance of oats into the diet, products that the consumer finds attractive are required. Knowledge of the raw material and how it behaves during processing is needed to enable the development of existing and novel processes. As has been shown in this literature, kilning and steam tempering are key stages of oat processing, which influence product stability, flavour and pasting. However, there is little published on how steaming influences the processability of oats or other quality parameters, such as water absorption and flake texture.

3. Objectives

The objective of this study was to clarify the effect of heat treatments on the quality of oat flakes. Flavour and flake stability are of course important quality aspects, but these have already been studied in some detail, so in this study flake texture and water absorption were considered.

The aims of the experiments were:

1. To test the assumption that kilning can improve the quality of oat flakes.
2. To determine the effect of heat on the dynamic mechanical properties of the oat groat during two heating cycles.
3. To determine the effect of steaming on the strength of oat groats in compression, thus testing the results of the non-destructive dynamic measurement and moving them closer to the reality of mill processing.
4. To determine the relationship between the mechanical properties of the oat groat and flake quality.

4. Materials and Methods

A general overview of the materials and methods is given below. More details are presented in the original publications (I – IV).

4.1. Effect of kilning on the strength of oat flakes (I)

The effect of kilning was tested by preparing oat flakes at three levels of thickness from kilned and unkilned groats at a commercial mill (Myllyn Paras Ltd., Hyvinkää, Finland). Kilning was for 2.5 hours at 85°C, and all samples were steamed and tempered for 45 minutes before flaking.

4.1.1. Using the equilibrium moisture content to temper samples

Flakes (about 5 g) were accurately weighed into oven moisture dishes and dried in an evacuated desiccator over phosphorus pentoxide. When the flakes had reached a stable weight, they were assumed to be totally dry. They were then transferred to another evacuated desiccator, which contained saturated salt solution that was used to regulate the relative humidity (LiCl 11.5%, CH₃COOK 23.4%, MgCl₂ 32.9%, K₂CO₃ 44.3%, Mg(NO₃)₂ 53.6%, NaNO₃ 65.4%, NaCl 76.5%, KCl 84.8%). The samples were weighed periodically, until they reached a stable weight, from this the equilibrium moisture content was calculated.

4.1.2. Measurement of flake strength

Ten flakes with no obvious defects were selected and their thickness measured using a micrometer. Flake strength was measured with a Texture Analyser XT-2i (Stable Microsystems, Godalming, England) from individual flakes using a pin deformation test. A cylindrical probe with a diameter of 2 mm was driven through a flake that was placed crease down over a 3 mm hole, at a speed of 10 mm/s. Data was recorded to a computer at a rate of 500 points per second.

4.1.3. Scanning electron microscopy

The surface properties of oat flakes that had been selected as “typical” were investigated using scanning electron microscopy. Two flakes per sample were attached to aluminium stubs using conductive, double-sided tape and sputter coated with

gold. Samples were examined using a scanning electron microscope (JSM-840A, Jeol Ltd, Japan) at an accelerating voltage of 15kEV. Images of representative areas of the flake were recorded in digital format.

4.2. Dynamic rheological behaviour of oat groat (II)

The effect of heating and cooling on the mechanical properties of oat were tested from samples of regular thickness (0.8 mm) that were machined from individual groats. The machining technique was adapted from Haddad et al. (1998). A block of steel was machined so as to have a 1 mm groove on one side and a 0.8 mm groove on the other side. Fine emery paper was attached to a second steel block. Groats were cut into half along the crease and the cut surface was glued into the 1 mm groove. The groats were sanded until further abrasion did not result in flour. The groat pieces were detached and the sanded surface was then glued into 0.8 mm groove. The sanding process was repeated until no fresh flour was produced. Haddad et al. (1998) further machined pieces of wheat kernel to produce a regular geometric shape, but oats are less durable. It was decided that the benefits of a simplified geometry were outweighed by damage caused to the test piece by this further processing.

A sample prepared from cultivar Salo was used in preliminary tests. The moisture content of the samples was controlled by drying over phosphorus pentoxide and then allowing them to reach their equilibrium moisture content at three levels of relative humidity (11%, 44% and 76%) over saturated salt solutions. A sample of the cultivar Puhti was studied in detail at five levels of moisture content. Both samples were obtained from Boreal Plant Breeding (Jokioinen, Finland). To ensure that the results were not the result of sample drying during heating, dry samples were also tested.

For the preliminary study, sample area was crudely estimated from the product of the length and width of the groat, and the storage and loss moduli were thus reported in arbitrary units. In the reported study (II), sample area was obtained by image analysis using the AxioCam MR Grab V system (Carl Zeiss, Germany). Measurements were made using a Netzsch dynamic mechanical analyser 242 (Selb, Germany) over a temperature range -20 – 100°C, which was chosen to represent possible temperatures encountered during storage and processing. The target deformation was set at the minimum possible (7.5 μm), representing a maximum strain of 0.94%. The storage modulus (E'), loss modulus (E'') and phase angle ($\tan \delta$) were obtained. Measurements were made in triplicate.

To test whether the results were due to drying out of the sample, some test pieces were weighed before and after the measurement. It was observed that the weight changed constantly if the samples were exposed to ambient conditions. Thus, all

samples included in the reported results were transferred rapidly to the relatively confined space of the DMA measuring head. To eliminate the possibility that the results were exclusively due to drying, samples dried over phosphorus pentoxide were also analysed.

4.3. Dynamic rheological behaviour of tablets made from ground groat and starch (Unpublished data)

To further investigate the changes in the mechanical properties during heating, about 100 g of the sample was also ground in a cyclone mill (Cyclotec, Perten Instruments Ab, Huddinge, Sweden) and a 0.75 g portion of this was formed into a tablet with a diameter of 30 mm in a tablet press at 15 tonnes pressure for 3 minutes. Oat starch was extracted from the sample using the method of Paton (1977). The extracted starch was also formed into tablets.

Sample was cut from the centre of the tablet with a cork borer (diameter 10 mm) and tested using a multi-frequency programme in compression using a Netzsch dynamic mechanical analyser 242 (Selb, Germany) over a temperature range -20 – 100°C, as described above.

4.4. Mechanical properties of steamed groats (III)

Kilned and unkilned groats were prepared from a single batch of oats by Myllyn Paras Ltd. (Hyvinkää, Finland). The samples (about 20 kg) were stored in cool, dry conditions (10°C, 40% RH) in paper sacks. Small sub-samples were taken, as needed and warmed to room temperature before use (21 – 23°C).

A laboratory steamer was developed that enabled steam to be efficiently mixed with the groats. This consisted of a stainless steel outer cylinder, the exterior of which was insulated with glass wool. A loose fitting plastic lid held a copper steam pipe at the centre of the cylinder. Steam, initially at 2 bar, was passed through a droplet remover and was injected into the bulk of the groats by means of 6 perforations evenly distributed along the length of the pipe on either side of two mixer blades. The blades were slightly twisted, so that they lifted groats as the outer cylinder was slowly rotated by means of an electric motor.

Tempering was conducted in a steel container with a loosely fitting lid. The groats were stirred at the start and end of tempering, which was carried out in a laboratory oven. The temperature of the groats was measured at the end of tempering and a sample was placed in a sealed plastic bag for moisture determination.

The mechanical properties of 20 individual groats were measured using a uniaxial

compression test. The groats were placed crease down and compressed by 50% of the groat height using a 36 mm cylindrical probe driven at a speed of 1 mm/s by a Texture Analyser TA-XT2i (Stable MicroSystem, UK). A temperature controlled cabinet (Stable MicroSystems, UK) set at 65°C was used, to simulate the hot conditions during flaking.

Preliminary tests were performed to establish suitable steaming and tempering protocols. Two steaming times (15 and 30s), two oven temperatures (80 and 100°C) and two tempering times (30 and 90 min.). On the basis of these tests, a full factorial experimental design was used with a single steaming time (30 s) and three levels of oven temperature (80, 95, 110°C) and tempering time (30, 60, 90 min.).

4.5. Effect of steaming and tempering on flake quality (IV)

Groats were tempered as described above and flakes were produced using a laboratory scale flaking machine (Ames and Rhymer, 2003). The flaking machine was adapted to suit whole groats. Industrial flaking rolls are typically 400-500 mm in diameter compare with 70 mm for the experimental flaking machine. The increased curvature of the rolls resulted in frequent blockages. To alleviate this the rolls were treated to give them a matt surface, which gripped the groats and a relatively large gap (0.4 mm) was used.

The flakes were dried in a 1100 W vegetable drier (Marlemi Ltd, Lemi, Finland) at a temperature of 40±5°C. During preliminary tests the drying time was 15 min and this was increased to 25 min for the reported study.

4.5.1. Flake quality

Inactivation of enzyme activity was verified by extracting ground oat flakes (0.5 g) in water (100 ml) for 30 min. Peroxidase activity was determined by observing the formation of red colour in guaiacol, in the presence of hydrogen peroxide. Moisture content was determined from the ground flakes by oven drying at 130°C, using the ICC Standard method 110/1.

The specific weight was measured. Flake size and amount of fines was evaluated by sieving. Water absorption was determined by soaking 20 g of oat flakes in approximately 200 ml water for 5 minutes, and then allowing the flakes to drain for 5 min. in a Glutomatic sieve unit (Pertten Instruments Ab, Huddinge, Sweden).

Flake thickness was measured from 20 flakes and the strength of these flakes was determined as described above.

4.6. Industrial-scale trial (Unpublished data)

To verify the findings from the previous study, a industrial trial flaking was carried out at Polar Mills Ltd. (Vaasa, Finland). Unkilned, whole groats were flaked and groat temperature after steaming was varied between 85 and 98°C. A constant feed rate was used and roll gap was adjusted as necessary to maintain a constant specific weight (360 – 375 g/l). Groat temperature was determined immediately before flaking and a small sample (ca.100 g), for moisture determination, was sealed into a Minigrip® bag. Peroxidase activity was assayed from the groats to ensure that the flakes were stable. Moisture was determined the following day as described previously.

Flakes were sampled after the drying process, approximately 1.5 kg were sealed into Minigrip bags. The drier conditions were maintained constant throughout the experiment. The flake samples were analysed for specific weight, thickness, water absorption, strength and fines within a week of production, using the methods described in the previous section.

No true replicates were performed owing to time restraints and the high value of industrial process time.

5. Results

5.1. Water adsorption (I and II)

Oat flakes adsorbed water slowly; steady state equilibrium water content was reached in about 12 days in the case of ground oat flakes but took up to 47 days for whole flakes. No mould growth was observed in any of the samples during the time needed to reach equilibrium, although mould was observed after extended storage at $a_w > 0.75$. The Guggenheim-Anderson-de Boer (GAB) model, which is widely used to fit water sorption data from foods, fitted the data well. The monolayer values of whole flakes were invariably higher than for the same flakes when ground (Fig. 9). Monolayer values obtained from the GAB model were in the range 7.95 – 8.17 g/100g dry matter for whole flakes and 5.83 – 6.84 for ground flakes. The value for oat groat pieces was similar to those of ground flakes, 6.78 g/100 g dry matter. The relationship between relative humidity and equilibrium moisture content was used to control sample moisture in later experiments.

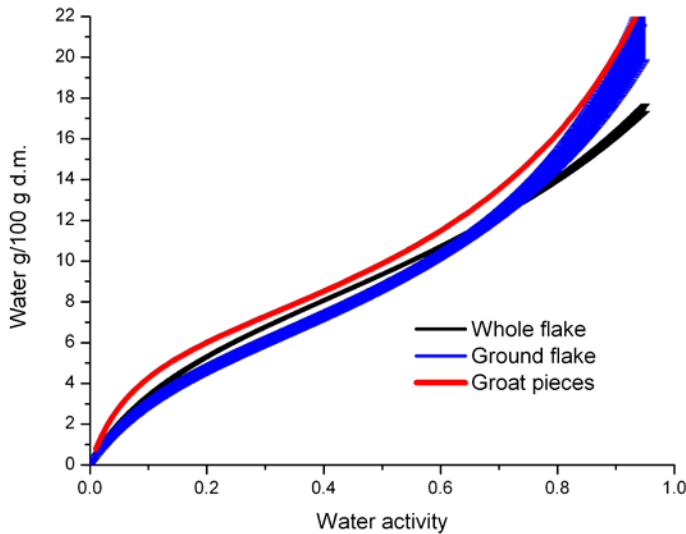


Figure 9. Water adsorption of oat groat pieces, flakes and ground flakes. Line thickness indicates standard deviation.

5.2. Effect of hydrothermal treatments on the mechanical properties of oat groats (II & III)

5.2.1. Dynamic mechanical analysis (II and unpublished)

Heating caused a marked increase in E' during first heating of oat groat pieces, but not during reheating (Fig. 10). During first heating from -20°C – 100°C , a minimum for E' was observed at 36°C – 57°C . Reheating was characterised by softening. The same general behaviour was observed in both cultivars (Puhti and Salo), but there were specific differences in that for the sample of Puhti at all temperatures E' was highest at a water activity of 0.44 during first heating and 0.65 during reheating, whereas the highest values were observed at water activity 0.11 for Salo. In both cases, the mechanical behaviour of oat groat was largely independent of frequency. Thus only the results from a single frequency (1 Hz) were further analysed.

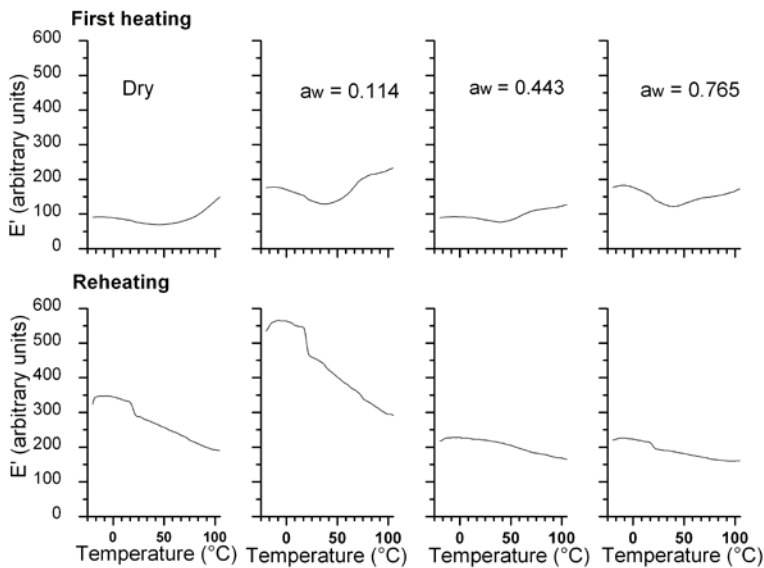


Figure 10. Average DMA curves showing the effect of water activity and temperature at 1 Hz for cultivar Salo (unpublished data).

The possibility that the stiffening of the kernel pieces was due to drying of the sample during the course of the test was considered. Samples did lose water during heating, indicated by a loss of mass. Grains are hygroscopic, and no steady weight was obtained most samples lost water during weighing, but dry samples took up

water from the air. For this reason the curves from weighed samples were not analysed. That the stiffening was also observed in samples that had been dried to constant weight over phosphorus pentoxide suggested that drying was not the main cause of stiffening. Furthermore, the extent of stiffening did not directly relate to initial water content.

The same type of behaviour was also observed in tablets prepared from ground groats and from starch (Fig. 11). However, there was a decrease in E' after about 80°C for the starch, whereas the oat continued to stiffen, which suggested that the phenomenon is not exclusively related to starch.

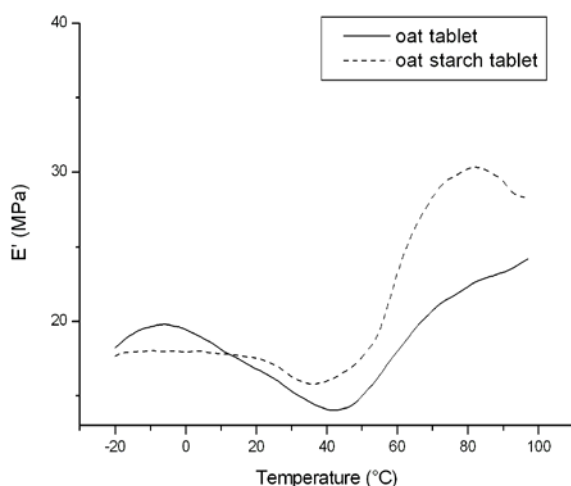


Figure 11. Example of DMA thermogram of tablets prepared from ground groats and oat starch during first heating (unpublished data).

5.2.2. Strength of oat groats under static loading (III)

Steaming made oat groats more compliant during uniaxial compression, and reduced breakage (Fig. 12). This was evidenced by a reduction in maximum force (strength) and the number of peaks (fracture events) that occurred during compression. Tempering conditions also influenced the mechanical properties of the groats. Higher oven temperatures resulted in an increase in groat strength, which agreed with results from DMA testing.

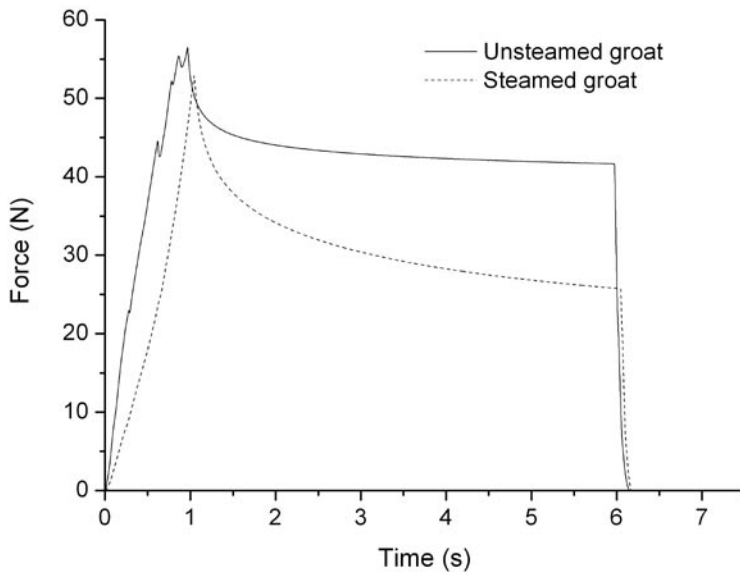


Figure 12. Examples of typical force-deformation curves for steamed and unsteamed oat groats.

5.3. Effect of processing on flake properties (I & IV)

5.3.1. Flake strength

Maximum force was used as a measure of flake strength. The maximum force of the thin flakes was observed at a larger deformation than for thick flakes, and at a point greater than the thickness of the flake. A probable explanation of this is that these flakes were sufficiently flexible to bend, and were thus forced into the hole in the supporting plate. Dry flakes failed in a brittle manner, indicated by a jagged peak; whereas, at high water content the flakes were less stiff and failed in a more plastic manner. Thin, moist flakes failed through a punch-like mechanism after being forced into the hole.

Tempering conditions did not directly affect flake strength (Table 2). Flake strength was, however, influenced by the groat strength, indicated by a significant correlation ($r = -0.361$, $P < 0.05$, $n = 54$) between these properties. Flake thickness was affected by tempering conditions and this influenced moisture content, as thick flakes dried slower than thin flakes. Thickness and moisture content also influenced the mechanism of flake breakage, and the correlation of thickness with flake strength ($r = 0.636$, $P < 0.001$, $n = 54$) was significant.

Table 2. Summary of analysis of variance for the effect of tempering parameters on groat and flake properties (Supplement to IV).

Source of variation	d.f.	Mean square										
		Groat temperature	Groat moisture	Groat height	Groat strength	Groat final force	Flake moisture	Flake specific weight	Flake thickness	Flake fines	Flake strength	Flake water absorption
Kilning (K)	1	22.69	39.70*	0.010	67.92	58.80	0.667	1185**	2535	0.167	0.026	6.000
Oven temperature (O)	2	210.4*	3.147	0.001	204.5*	127.6*	0.031	149.1	650.0	0.004	0.691	165.1***
Temper time (T)	2	20.62	5.872	0.001	112.1	72.80	0.237	41.72	1327	0.500*	0.117	85.17***
K x O	2	138.2	0.821	0.005	8.430	7.610	0.101	98.91	535.2	0.094	1.145	5.389
K x T	2	0.189	1.907	0.002	2.979	3.199	0.237	81.02	924.0	0.047	0.308	20.39
O x T	4	30.13	2.127	0.003	82.39	79.54	0.282	536.0**	8305*	0.136	1.351	33.22**
K x O x T	4	3.074	2.114	0.005	31.47	25.77	0.123	158.3	6090	0.161	0.746	11.28
Residual	36	49.48	4.568	0.007	48.47	35.34	0.394	115.6	2622	0.144	0.519	8.556

***, **, * P<0.05, 0.01, 0.001, respectively

5.3.2. Thickness and specific weight

The gap between the flaking rolls is clearly the main determinant of flake thickness, but in all cases flake thickness was greater than the gap between the rolls. Tempering conditions affected the mechanical properties of the groats, and an interaction between oven temperature and tempering time significantly affected flake thickness (Table 2). The size of the groat also correlated weakly ($r = 0.310$) with flake thickness.

Kilning had a small, but significant effect on specific weight, which was slightly higher for the flakes prepared from kilned groats. Oat millers often rely on specific weight to predict flake thickness, and there is a highly significant correlation between these properties. However, when different processing conditions are used, the correlation coefficient was only 0.808, which is not strong enough to indicate the ability of specific weight to predict of flake thickness.

5.3.3. Flake sieving

Particles that pass through a 2.5 mm sieve were considered as fines. This fine material consisted of fluff, derived from the trichomes, and small chips of broken material that accounted for most of the mass. The 5 mm sieve retained mostly unbroken flakes derived from whole groats. A linear increase in breakage was observed with tempering time. The amount of fines did not correlate with the other properties measured.

5.3.4. Surface characteristics of oat flakes (unpublished)

The surface of the flakes appeared to be partially covered in fragmented pieces of the bran, with areas of endosperm exposed. There was considerable variation between flakes within a single sample, and even between different regions of the same flake. Samples from thick flakes tended to have less endosperm exposed than thin flakes (Fig. 13). No differences were noticed between kilned and unkilned samples produced at the same mill.

5.3.5. Water absorption

Water absorption increased with oven temperature and tempering time (Table 2). Surprisingly, it did not relate to flake thickness but it did correlate weakly with flake strength ($r = -0.274$, $P < 0.05$, $n = 54$) and groat strength ($r = 0.397$, $P < 0.01$, $n = 54$). Its correlation with the amount of fine material was not significant, because this

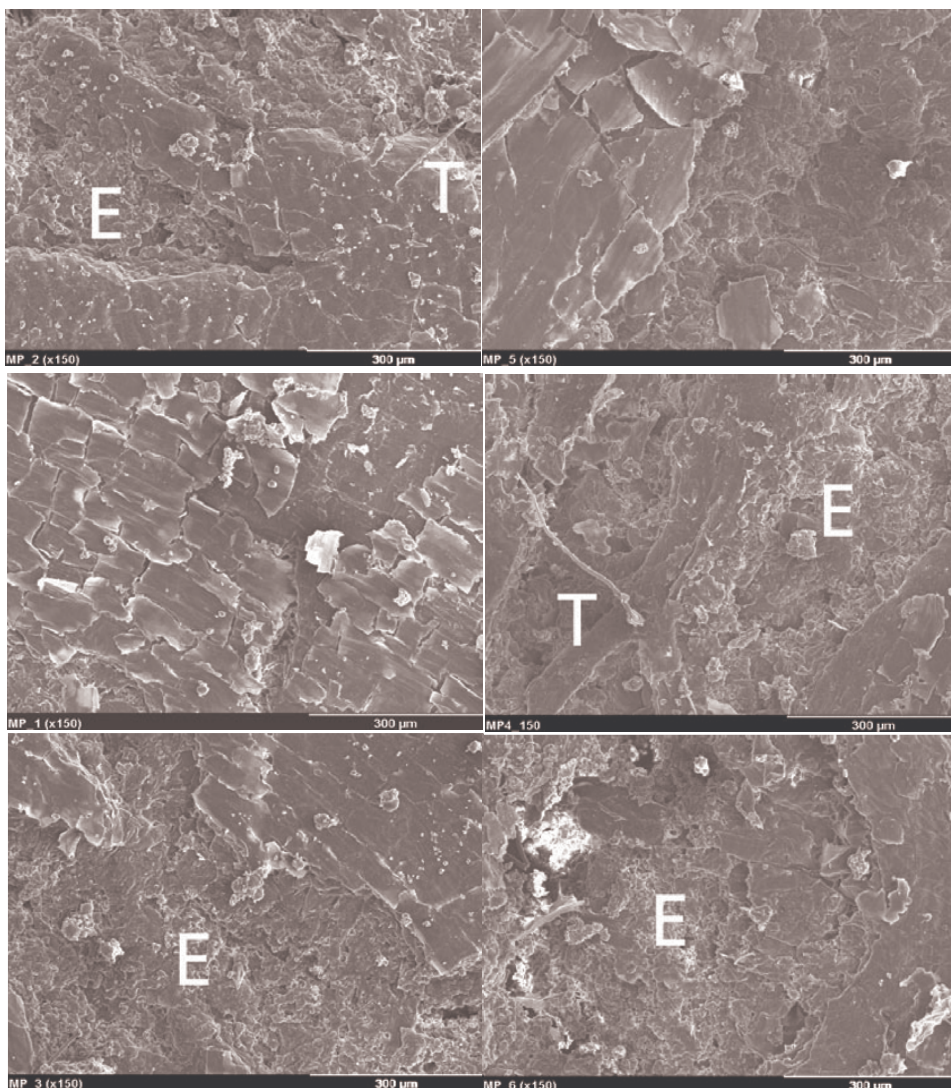


Figure 13. Typical scanning electronmicrographs of the surfaces of oat flakes (x150). T indicates a trichome and E exposed endosperm. Unkilned flakes are on the left and kilned flakes on the right. Flake thickness increases from top to bottom.

was removed before the determination of water absorption.

5.4. Effect of groat temperature on industrially produced flakes

Flake specific weight was maintained almost constant throughout the experiment, although it was lower in sample 3, and the flakes were correspondingly thinner

(Table 3). This sample was not repeated since the flakes still retained some peroxidase activity and were therefore not suitable for food uses. The flakes produced from groats at the lowest temperature (85°C) were considerably weaker than the other samples, but this did not result in an increase in the amount of fine material during sieving.

Table 3. Experimental design for industrial flaking trial.

Samples in order of production	Setpoint (°C)	Peroxidase	Groat temperature (°C)	Specific weight (g/l)	Flake thickness (mm)	Flake strength (N)	Fines (<2 mm) (%)
1	100	Not detected	92	368	0.80	3.67	1.36
2	97	Not detected	88	368	0.84	3.91	0.66
3	97	Trace	85	360	0.80	3.22	0.50
4	101	Not detected	96	375	0.85	3.94	0.56
5	101	Not detected	98	373	0.84	3.94	0.56

Water absorption generally increased with groat temperature to a maxima at 96°C (Fig. 14). Contrary to what would be expected, the lowest water absorption was obtained from the sample with the thinnest flakes. This suggested that structural differences, which will be discussed later, were responsible.

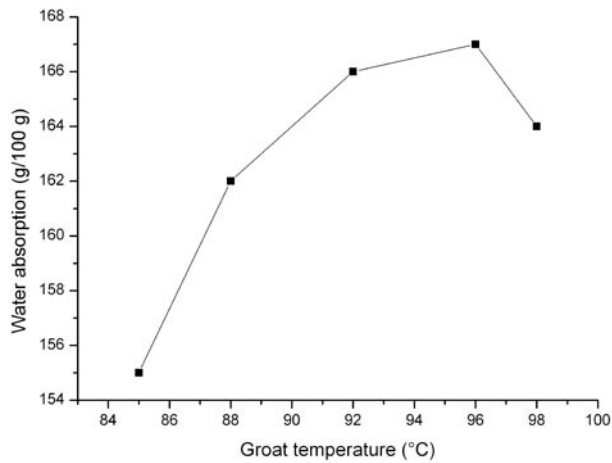


Figure 14. Effect of groat temperature on water absorption of oat flakes.

6. Discussion

The results showed the influence of heat treatment on oat groat and flake properties. Starting with an empirical study of the effect of kilning on flake strength, the influence of heat processing on oat flake quality was investigated. Dynamic mechanical analysis provided a tool for measuring changes in the structure of oat materials at the macromolecular level. Empirical measurements with a Texture Analyser were used to link changes in the mechanical properties of oat groats during steam tempering with their behaviour during flaking. This necessitated the development of a laboratory scale steaming protocol. The properties of flakes produced from these groats was determined after flaking with a benchtop machine. Since there were unavoidable differences between the laboratory system and industrial practice, the results were verified using an industrial trial.

The use of industrial trials is fraught with difficulties. Commercial mills have high capacities, so the amount of trial material is inevitably large, generally in the order of hundreds of kilos, if not tonnes. This precludes large changes in process variables that risk the production of unsellable material. This is especially the case if there is even the slightest risk of damaging the processing equipment. Interactions between the process variables and non-linear responses create further complications. With a very small number of tests, performed without replication, it is impossible to interpret the results of these trials in a scientific sense. This work shows how laboratory scale equipment can be used in conjunction with other techniques to gain insight into the oat flaking process.

6.1. Flake quality and how to measure it

6.1.1. Stability

Flake stability is probably the most important factor defining the quality of oat flakes. Unless the enzyme systems of the oat are inactivated, the flakes develop bitter or soapy flavours. For this reason steaming is a key part of the food processing of oats, and enzyme activity is determined, usually by measuring peroxidase activity. Industrially kilned samples still had a low level of residual peroxidase activity (IV), confirming previous studies (Ekstrand et al., 1992; Zhou et al., 1999). Ekstrand et al (1992) found that peroxidase was more heat-stable than lipase during steam treatment and during oven drying, but Vorwerck (1988) reported that peroxidase was less stable than lipase. Vorwerck did not give details of how the enzyme activities were determined, so it is not possible to explain this difference.

Considerably milder steaming conditions than those encountered in industrial kilning were found to be sufficient to inactivate lipolytic enzymes (IV). Under laboratory conditions, steaming for 30 s, followed by a tempering period of 30 min. at a temperature of 80°C inactivated peroxidase. Even 20 s of steaming was sufficient providing that the oats were tempered at 100°C for 30 min. Perhaps the longer tempering times in the industrial process are necessitated by the difficulty of mixing a large volume of grain to ensure even temperature and moisture distribution.

6.1.2. Specific weight

Millers use specific weight as a measure of flake thickness, and it is equally important in its own right as it determines the fill volume of the pack. Specific weight determined in containers with different geometries was shown to be comparable, providing the filling procedure was the same (i.e. free flow of flakes was allowed). Although the correlation between flake thickness and specific weight was highly significant (IV), processing conditions influenced the relationship between these properties. Since industrial users, such as biscuit or breakfast cereal producers, generally require compliance across a range of quality measures (e.g. specific weight, water absorption and flake texture), it may be possible to make fine adjustments to product quality by means of the heat treatment.

6.1.3. Water absorption

For some end uses, water absorption is critical. In biscuit making, it is a factor in the consistency of the dough, and as such influences the size and shape of the biscuit. In muesli, the absorption of milk greatly influences the texture of the product. The method for determining water absorption varies between companies. A standard method has been issued by the American Association of Cereal Chemists (AACC 56-40), but this has a number of points that makes it unsuitable for routine use in quality control. The need to use a standard sieve, tilted at an angle of 45° requires a large amount of bench space, and in practice restricts the number of determinations that can be carried out simultaneously. Also the temperature of the water greatly influences water absorption. In the AACC method, the temperature of the water should be 74°F (23.3°C), which is difficult to achieve as laboratory temperature often varies considerably between summer and winter. The large sample size (50 g) also presented a problem, as the capacity of the experimental mill was limited. For these reasons the method was modified, based on methods currently used by some European manufacturers.

A water temperature of 30°C was selected as this is easy to control by means of a water bath, which is commonly set to this temperature for other cereal testing

methods (e.g. Farinograph). The Glutomatic is widely used by mill laboratories, and its sieving units are small and can be conveniently placed over a beaker. Soaking time was selected on the basis of currently used methods. The initial rate of water uptake is relatively fast but the rate slows as equilibrium is reached. Sufficient time should be allowed for excess water to drain from the flakes, but should not be unnecessarily long. The method developed in this study had several practical advantages over the AACC method, particularly in reducing the amount of bench space required and was used to measure the water absorption of flakes produced from the experimental mill (IV).

6.2. Comparison between the experimental system and industrial steaming

To test the effect of process parameters on flake quality, a laboratory scale flaking process was developed. Kilning was carried out at a commercial mill, as this operation is independent of the rest of the flaking process and was convenient to carry out at the mill. There was little difference between flakes made from kilned and unkilned groats (I). For this reason, no attempt was made to vary kilning conditions in the experiments.

At the start of the industrial flaking operation, steam is added at a single point to a continuous stream of groats. The temperature of the groats is determined a little after steam injection and a feedback loop is used to control a valve so that a target temperature is maintained in the groat bulk. It is therefore difficult to estimate the duration of steaming. The groats are mixed at the top of the steamer and then pass into the tempering region in which they remain for 15 min. or more (Ganssmann and Vorwerck, 1995).

The steam used in the experimental system (III; IV) was at a similar pressure (2 bar) to that used in the industrial process. Steam was directly injected into the groat bulk and mixing ensured the even distribution of heat and moisture. The flow of steam was controlled by a valve, and was kept constant throughout the experiment. In commercial mills the flow is controlled so as to achieve a set groat temperature. The experimental system was a batch operation, because of the difficulty of maintaining a constant flow of groats in a small unit. Especially when dampened, the groats stick together and tend to clog the system. For safety reasons, it was not possible to maintain a constant flow of steam during the filling of the unit and as a result the steam pipes and chamber cooled making the initial phase of steaming quite wet. This limited the minimum steaming time to about 30 s. Tempering was carried out as a separate operation.

6.3. Influence of heat processing on flake quality

6.3.1. Water adsorption and flake strength

Stability, texture and other properties of cereal-based foods are related to their water content, and since food is hygroscopic this is related to relative humidity of the surroundings. The relationship between water activity and equilibrium moisture content is thus of interest, and is often presented as a sorption isotherm. The equilibrium moisture content also provides a convenient way of regulating the water content of a sample in a controlled and repeatable manner. This can conveniently be achieved under vacuum in a desiccator containing a saturated salt solution, and tables of the equilibrium relative humidities of saturated salt solutions are available (Labuza et al., 1985).

The GAB monolayer values (5.83 – 6.84 g/100 g) for oat flakes (I) were higher than those reported by Jensen and Risbo (2006) who gave a value of 5.5 g/100g for undried oat meal. They were also considerably higher than the 3.36 g/100g reported for oat flakes oven dried at 105°C (McMinn et al. 2007). Strange and Onwulata (2000) reported a value of 5.33 g/100 g for oat fibre. This is probably the result of sample history affecting sorption behaviour.

Many cereal foods are crisp or crunchy at low moisture content but at higher water activity become soft. This has been connected with the stiffness of the material and explained in terms of the glass transition (Peleg, 1993; Roos et al., 1998) . Water activity has little effect when the material is in the crisp (glassy) state or in the fully plasticised (rubbery) state, and the transition between these two states is relatively sharp. This type of behaviour explains the loss of strength observed in the thick and medium flakes (I).

Thin flakes, however, showed an unusual strengthening of the flakes at water activity 0.44 (I), and this was also observed in groats in the DMA study (II). Stiffening at intermediate water contents has been previously reported in cereal based products, and although this phenomenon is not yet fully understood, but it appears to be related to changes in the microstructure of the flake and possibly to changes at the macromolecular level (Harris and Peleg, 1996; Gonddek and Lewicki, 2006; Marzec and Lewicki, 2006). As well as allowing increased molecular mobility, water swells macromolecules. This has the effect of eliminating cracks and flaws in the structure, which especially in brittle materials weaken the material (Dobraszczyk, 1994).

Flake strength was influenced by the mechanical properties of the groat, indicated by a significant correlation ($r = 0.636$) between these properties (IV). These in turn are dependent on processing conditions (IV) and on genetic and agronomic back-

ground of the oats (Doehlert and McMullen, 2000; Peltonen-Sainio et al., 2001). There is also an indirect influence of heat processing on flake strength, through its effect on flake thickness.

6.3.2. Moisture content and water absorption

The movement of water out of the flake during drying and into the flake during food processing (water absorption) has implications on quality. Flake thickness influences the rate of diffusion of water during drying. This was reflected by a significant, albeit weak correlation between flake thickness and moisture content (IV). Surprisingly, over the range of thickness obtained from a single roll gap, thickness did not correlate with water absorption ($r = -0.202$). This supports the findings of Machado et al. (1998), who found that moisture uptake of extruded breakfast cereal flakes was mainly a relaxation rather than a diffusion phenomenon. This is analogous to mechanical relaxation tests, widely used in material testing. When the flakes are immersed in water they act as a perturbing “force”, displacing water. The structure of the flake acts as a barrier, opposing the forces that act to restore the system. Initially the flake will absorb water rapidly, but as it approaches equilibrium the rate will decrease. This can be modelled as an exponential decay. The advantage of applying this type of response theory is that it allows the study of non-equilibrium dynamic responses, in which it is impossible to account for all transient effects (Dattagupta, 1987). Thus structural features, such as the presence of flaws that allow for the rapid movement of water or a glossy surface that impedes it, are more important than thickness. This is further supported by the presence of a significant, weak negative correlation ($r = -0.274$) between flake strength and water absorption (IV).

Tempering conditions had a significant effect on water absorption, which increased with oven temperature and tempering time (IV). Oeding (1996) found that higher steam temperature and groat moisture during steaming resulted in increased water absorption, and suggested that this was related to changes in pasting behaviour. This offers a complementary, or possibly alternative, hypothesis based on the water binding of the macromolecular components. However DMA studies of changes occurring in starch tablets during heat treatment, which will be discussed in more detail later, are consistent with a structural explanation.

6.3.3. Breakage and size

Sieving was used to characterise flake size and breakage. Other things being equal, the size of the flakes is related to the the spread of the groat during flaking (thickness) and breakage. Thick flakes do not have as great a surface area after flaking, but will be less prone to breakage than thin flakes. Perhaps because of the complexity of this relationship, there was no significant linear relationship between flake or groat properties and size distribution. However, there was a significant relationship between tempering time and flake breakage (IV).

A linear increase in breakage was observed with tempering time (IV). Ganssmann and Vorwerck (1995) reported that flake breakage was reduced by using a longer tempering time, but the times used in their study (0 – 35 min.) were much shorter than those used in these studies (III, IV). In addition, in their study that there was a slight increase in breakage between 25 and 35 minutes tempering (Ganssmann and Vorwerck 1995). Another German study by Oeding (1996) used tempering times between 5 and 15 minutes, and found that breakage was mainly influenced by steam temperature, and he postulated that the formation of a glossy layer due to starch pasting at the surface protected the floury endosperm, preventing attrition from weakening the flake.

6.4. Structure and mechanisms in the flaking of oats

6.4.1. Structure of the groat in relation to flaking

Oats, unlike most other cereals, have traditionally been used mainly as flakes. It is also interesting that no moisture induced brittle-ductile transition was observed in oat groats, as has also been noted by Engleson and Fulcher (2002b). In study II no glass transition was observed, nor was there any marked softening of the groat with increasing moisture content over the range studied. If a cold groat is compressed a crude flake is formed. Its structure is softer and slightly waxy and it is more prone to break than a flake made from steamed groats (results not shown). This propensity to flake is probably related to the structure of the oat groat. In particular, the absence of a continuous protein matrix allows for freer movement of starch granules in the endosperm during flaking than is the case in other cereals such as wheat. This results in the observed ductile behaviour of oat groats.

As the groat passes between the flaking rolls, it is deformed at various structural levels. Overall, material is forced to spread away from the leading edge and side-

ways (Levine and Levine, 1997). This suggests that starch granules move relative to each other, which deforms the cell walls in the endosperm and overall the structure is compacted. The starch granules and protein bodies are also deformed and these may be damaged (Lookhart et al., 1986). At small deformations, the mechanical properties of the groat are due mainly to an interaction between the mechanical properties of the cell walls and the strength of the bond between starch granules. As the deformation is increased, the properties of the starch granules and protein bodies will become increasingly relevant.

6.4.2. Heat induced changes in starch tablets and groats

Marked stiffening of oat groat pieces was observed during heating from -20°C to 100°C in a DMA (II), which did not appear to be associated with drying of the sample. To further investigate this phenomenon, ground groats and extracted starch were formed into tablets. Tableting involves the compaction of a powder, which increases the contact between the particles and allows bonding to occur, this includes polar interactions and hydrogen bonding. Interfaces are thermodynamically unfavourable, and thus surface energy also causes cohesion at the contacting surfaces in the absence of a repulsive force (Hiestand, 1997). The contents of the endosperm cells also represent a compact structure, with starch granules and protein bodies in close proximity (Fulcher, 1986). A striking similarity was observed between thermograms of oat starch tablets and groat pieces, suggesting that the same phenomenon occurs in the oat groat.

Whether this stiffening is the result of changes in the granule structure of starch or the interaction between the granules is not directly evident. The hardness of a tablet is manifested primarily as the plastic deformation of the compact under an indenter (Hiestand, 1997). Although the viscoelastic properties play a role in the mechanical properties of tablets their contribution is likely to be small, compared with the bonding between the particles (Hiestand, 1997). Thus it can be inferred that the observed stiffening at the macroscopic scale in groats (III) is probably the result of increased adhesion between starch granules.

Increased adhesion between starch granules will increase the stiffness and result in a more brittle material. Brittle fracture is the result of the concentration of stress at the tip of a crack (Griffith, 1920). The energy required for the fracture comes from the elastic deformation of the material, the stiffer the material the more energy will be stored for any given deformation. Plastic deformations, such as the slipping of starch granules, serve to dissipate energy, and increase the toughness. Cracks readily propagate in brittle materials. An increase in fine material would be expected to relate to brittleness, and this was observed as tempering time increased (III). As

explained earlier, increased water absorption (IV) is probably also related to the presence of flaws, and supports the hypothesis that heating increases the bonding between the contents of the endosperm cell. Although starch gelatinisation was not observed to occur in the majority of starch granules, it is possible that a small amount of starch leached and was able to increase the adhesion between starch granules.

6.4.3. Role of cell walls and bran

An alternative, or complementary explanation, involves the cell walls of the endosperm and the bran layers. As suggested earlier, cell walls also play a role in determining the mechanical properties of the groat. This can be inferred from the link between beta-glucan content, groat hardness and impact damage during hulling (Doehlert and McMullen, 2000; Engleson and Fulcher, 2002a). In the results reported in this thesis, steaming reduced groat strength and also made the groats more plastic. Since beta-glucan, a major component of oat endosperm cell walls, has a great affinity for water, it seems that the water will be transported into the endosperm using the cell walls as channels (Fincher and Stone, 1986). This may also partly explain observation that steaming is used to soften the groats and facilitate flaking, but an increase in groat strength is observed with increasing time and temperature during tempering. This additional water may also allow localised gelatinisation of starch.

The pericarp or bran layer also plays a role in the impact damage of oat groats during hulling (Engleson and Fulcher, 2002a), as well as in maintaining the integrity of flakes (McDonough et al., 1997). Steam softens the bran, and gelatinises starch near the surface of the groat, which helps the bran to adhere to the surface. This protects the flake from attrition and results in less disintegration. This hypothesis was partially confirmed by the observation that thick, glossy muesli flakes had a fairly intact bran layer on the surface, whereas the bran layer of more floury flakes was crazed and in places missing. Also, during extended tempering at high temperature, the surface of the groat would tend to dry. Observations that support this include the increase in the level of fine material with tempering time and the increased water absorption with both increasing tempering time and temperature.

7. Conclusions

1. Kilning had little effect on flake properties and did not totally inactivate the enzyme systems of the groats. However, the steam tempering process associated with flaking was shown to influence flake properties. As expected, steaming softened the oat groats and reduced the tendency to fracture.

2. Heating above about 55°C caused a permanent increase in the stiffness of oat groats. This stiffening was suggested to be due to increased adhesion between starch granules. Tablet strength has been shown to relate to the adhesion of the particles within the tablet rather than on the mechanical properties of the particles.

3. Experimental results also confirmed that the strength of oat groats increased with oven temperature. Cold flaking of oats resulted in weak, powdery flakes, but only small differences were observed in the strength of steam treated flakes. This is consistent with the stiffening effect occurring at a temperature at relatively low temperature. Trial milling at a commercial mill also indicated that water absorption related to groat temperature after tempering. This indicates that steam processing induced structural changes in the groat, and that these are relevant to industrial oat processing.

4. The literature suggests that water absorption is mainly restrained by the barrier properties of the flake. The presence of flaws allow water to penetrate the flake more rapidly and to be trapped in the structure of the flake, and thus result in a higher water absorption. An increase in water absorption would thus be consistent with an increased number of flaws in the structure. Longer tempering at higher temperatures led to an increase in water absorption. This was supported by an increase in the amount of fine material produced as tempering time increased. This would imply that the increased stiffness is due to increased bonding between granules.

The results from this study, if applied to industrial scale processes, could be used to save energy as well as to assist millers in providing flakes to customers with specific quality requirements. By optimising the heat treatment, in many cases an increase in the capacity of existing heat processing equipment is possible. It is also possible that by reducing the severity of the heat treatment, the nutritional properties of oat flakes may improve, as there would be less loss of Vitamin B1.

Future work should examine how these heat induced changes relate to the industrial processing of oat flakes. One aspect that was not considered in this study was the behaviour of oat flakes during cooking. Structural changes may also be relevant to the health benefits, as they may affect the extractability of bioactive components from the matrix.

8. References

- Aaltonen, J.; Järvenpää, M.; Klemola, E.; Laurila, I. P. Viljan korjuu-, kuivaus-, ja logistiikkakustannukset Suomessa. *Maatalouden taloudellisen tutkimuslaitoksen selvityksiä* **1999**, 2/99, 22 p.
- Ames, N. P.; Rhymer, C. R. Development of a laboratory-scale flaking machine for oat end product testing. *Cereal Chem.* **2003**, 80, 699-702.
- Bakker-Arema, F. W. Heat and mass transfer aspects and modeling of dryers. In *Concentration and drying of foods* Vol. D. MacCarthy, Ed.; Elsevier Applied Science: London, 1986; pp 165-202.
- Browne, R. A.; White, E. M.; Burke, J. I. Hullability of oat varieties and its determination using a laboratory dehuller. *J. Agric. Sci.* **2002**, 138, 185-191.
- Browne, R. A.; White, E. M.; Burke, J. I. Effect of nitrogen, seed rate and plant growth regulator (chlormequat chloride) on the grain quality of oats (*Avena sativa*). *J. Agric. Sci.* **2003**, 141, 249-258.
- Cenkowski, S.; Pronyk, C.; Zmidzinska, D.; Muir, W. E. Decontamination of food products with superheated steam. *Proceedings of the 2nd CIGR Section VI International Symposium on Future of Food Engineering, Warsaw, Poland, 2006*; pp.
- Christensen, C. M.; Miller, B. S.; Johnston, J. A. Moisture and its measurement. In *Storage of cereal grains and their products* Vol. C. M. Christensen, Ed.; American Association of Cereal Chemists: St. Paul, MN, 1982.
- Colleoni-Sirghie, M.; Jannink, J.-L.; White, P. J. Pasting and thermal properties of flours from oat lines with high and typical amounts of beta-glucan. *Cereal Chem.* **2004**, 81, 686-692.
- Dattagupta, S. *Relaxation phenomena in condensed matter physics*; Academic Press: London, 1987; 309 p.
- Dieter, G. E. *Mechanical metallurgy*, 3rd ed.; McGraw-Hill Book Co.: New York, 1986; 751.
- Dobraszczyk, B. J. Fracture mechanics of vitreous and mealy wheat endosperm. *J. Cereal Sci.* **1994**, 19, 273-282.
- Dobraszczyk, B. J.; Vincent, J. F. V. Measurement of mechanical properties of food materials in relation to texture: the materials approach. In *Food Texture: Measurement and Perception* Vol. A. J. Rosenthal, Ed.; Aspen Publishers, Inc.: Gaithersburg, 1999; pp 99-151.
- Doehlert, D. C.; McMullen, M. S. Genotypic and environmental effects on oat milling characteristics and groat hardness. *Cereal Chem.* **2000**, 77, 148-154.
- Doehlert, D. C.; McMullen, M. S. Optimizing conditions for experimental oat dehulling. *Cereal Chem.* **2001**, 78, 675-679.
- Doehlert, D. C.; McMullen, M. S. Identification of sprout damage in oats. *Cereal Chem.* **2003**, 80, 608-612.
- Doehlert, D. C.; McMullen, M. S.; Baumann, R. R. Factors affecting groat percentage in oat. *Crop Sci.* **1999**, 39, 1858-1865.
- Doehlert, D. C.; McMullen, M. S.; Jannink, J.-L.; Panigrahi, S.; Huanzhou, G.; Riveland, N. R. Evaluation of oat kernel size uniformity. *Crop Sci.* **2004**, 44, 1178-1186.
- Doehlert, D. C.; McMullen, M. S.; Riveland, N. R. Sources of variation in oat kernel size.

- Cereal Chem.* **2002**, *79*, 528-534.
- Doehlert, D. C.; Zhang, D. C.; Moore, W. R. Influence of heat pretreatments of oat grain on the viscosity of flour slurries. *Journal of Food and Agriculture* **1997**, *74*, 125-131.
- Donhowe, E. T.; Peterson, D. M. Isolation and characterization of oat aleurone and starchy endosperm protein bodies. *Plant Physiol.* **1983**, *71*, 519-523.
- Drapon, R. Enzyme activity as a function of water activity. In *Properties of water in foods in relation to quality and stability* Vol. D. Simatos and J. L. Multon, Eds.; Martinus Nijhoff Publishers: Dordrecht, 1985.
- Ekstrand, B.; Gangby, I.; Åkesson, G. Lipase in oats-distribution, pH dependence, and heat inactivation. *Cereal Chem.* **1992**, *69*, 379-381.
- Ekstrand, B.; Gangby, I.; Åkesson, G.; Stöllman, U.; Lingnert, H.; Dahl, S. Lipase activity and development of rancidity in oats and oat products related to heat treatment during processing. *J. Cereal Sci.* **1993**, *17*, 247-254.
- Engleson, J. A.; Fulcher, R. G. Mechanical behavior of oats: specific groat characteristics and relation to groat damage during impact dehulling. *Cereal Chem.* **2002a**, *79*, 790-797.
- Engleson, J. A.; Fulcher, R. G. Mechanical behavior of oats: the groat effect. *Cereal Chem.* **2002b**, *79*, 787-789.
- Eurola, M.; Hietaniemi, V.; Kontturi, M.; Tuuri, H.; Pihlava, J.-M.; Saastamoinen, M.; Rantanen, O.; Kangas, A.; Niskanen, M. Cadmium Contents of Oats (*Avena sativa* L.) in Official Variety, Organic Cultivation, and Nitrogen Fertilization Trials during 1997-1999. *Journal of Agricultural and Food Chemistry* **2003**, *51*, 2608-2614.
- FAOSTAT Core consumption data. <http://faostat.fao.org/site/346/DesktopDefault.aspx?PageID=346>. Accessed 27.11.2006.
- Fincher, G. B.; Stone, B. A. Cell walls and their components in cereal grain technology. In *Advances in Cereal Science and Technology* Vol. 5; American Association of Cereal Chemists: St. Paul, MN., 1986; pp 207-295.
- Foster, G. H.; Tuite, J. Aeration and stored grain management. In *Storage of Cereal Grains and Their Products* Vol. C. M. Christensen, Ed.; American Association of Cereal Chemists: St. Paul, MN., 1982; pp 117-143.
- Fulcher, R. G. Morphology and chemical organization of the oat kernel. In *Oats: Chemistry and Technology* Vol. F. H. Webster, Ed.; American Association of Cereal Chemists: St. Paul, MN., 1986; pp 47-74.
- Galbraith, D. Oat perspective of end user quality standards. *5th Manitoba Agronomists Conference, Winnipeg, Manitoba*; University of Manitoba, 2004; pp 14-16.
- Galliard, T. Enzymic degradation of cereal lipids. In *Lipids in Cereal Technology* Vol. P. J. Barnes, Ed.; Academic Press: London, 1983; pp 111-147.
- Ganssmann, W.; Vorwerck, K. Oat milling, processing and storage. In *The oat crop: Production and utilization* Vol. R. W. Welch, Ed.; Chapman and Hall: London, 1995; pp 369-408.
- Gates, F.; Sontag-Strohm, T.; Salovaara, H. Prosessin vaikutus kaurahiutaleisiin. In *Kaurasta Elinvoimaa* Vol. 1221: H. Salovaara and T. Sontag-Strohm, Eds.; Elintarviketeknologian laitokset: Helsinki, 2001; pp 127-140.
- Gates, F. K.; Dobraszczyk, B. J. Mechanical properties of oats and oat products. *Agricultural and Food Science* **2004**, *13*, 113-123.

- Gates, F. K.; Talja, R. A. Effect of temperature and moisture on the mechanical properties of oat. *Trans. ASAE* **2004**, *47*, 1223-1227.
- George, J.; McCracken, K. J. Changes in *in vitro* viscosity (IVV) of whole or ground wheat grain during storage and effects of storage temperature. *J. Cereal Sci.* **2003**, *37*, 179-185.
- Gondek, E.; Lewicki, P. P. Antiplasticization of cereal based products by water. Part II: Breakfast cereals. *J. Food Eng.* **2006**, *77*, 644-652.
- Griffith, A. A. The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society of London A* **1920**, *221*, 163-198.
- Groh, S.; Kianian, S. F.; Phillips, R. L.; Rines, H. W.; Stuthman, D. D.; Wesenberg, D. M.; Fulcher, R. G. Analysis of factors influencing milling yield and their association to other traits by QTL analysis in two hexaploid oat populations. *Theor. Appl. Genet.* **2001**, *103*, 9-18.
- Harris, M.; Peleg, M. Patterns of textural change in brittle cellular cereal foods caused by moisture sorption. *Cereal Chem.* **1996**, *73*, 225-231.
- Haydanek, M. G.; McGorin, R. J. Oat flavor chemistry: Principles and prospects. In *Oats: Chemistry and Technology* Vol. F. H. Webster, Ed.; American Association of Cereal Chemists: St. Paul, MN, 1986; pp 335-369.
- Hiestand, E. N. Principles, tenets and notions of tablet bonding and measurements of strength. *European journal of pharmaceuticals and biopharmaceutics* **1997**, *44*, 229-242.
- Hietaniemi, V.; Kontturi, M.; Rämö, S.; Eurola, M.; Niskanen, M.; Saastamoinen, M. Contents of tricothecenes in oats during official variety, organic cultivation and nitrogen fertilisation trials in Finland. *Agricultural and Food Science* **2004**, *13*, 54-67.
- Holkko, E.; Palva, R. "Viljan kuivaaminen keskitetysti - teollisuuskuivurihanke Etelä-Pohjanmaalla [Centralised grain drying - the industrial grain dryer in Southern Ostrobothnia]" TTS Institute, 2003.
- Hoover, R.; Vasanthan, T. The effect of annealing on the physicochemical properties of wheat, oat, potato and lentil starches. *Journal of Food Biochemistry* **1994**, *17*, 303-325.
- Hoseney, R. C. *Principles of cereal science and technology*, 2nd ed.; American Association of Cereal Chemists: St. Paul, MN, 1998; 378.
- Hsu, K. H. A theoretical approach to the tempering of grains. *Cereal Chem.* **1984**, *61*, 466-470.
- Hutchinson, J. B. Factors affecting the suitability of oats for processing. *Chemistry and Industry* **1953**, 578-581.
- Hutchinson, J. B.; Martin, H. F.; Moran, T. Location and destruction of lipase in oats. *Nature* **1951**, *167*, 758-759.
- Jayas, D. S.; Alagusundaram, K.; Shunmugam, G.; Muir, W. E.; White, N. D. G. Simulated temperatures of stored grain bulks. *Canadian agricultural engineering* **1994**, *36*, 239-245.
- Jayas, D. S.; White, N. D. G. Storage and drying of grain in Canada: low cost approaches. *Food control* **2003**, *14*, 255-261.
- Jensen, P. N.; Risbo, J. Oxidative stability of snack and cereal products in relation to moisture sorption. *Food Chem.* **2007** *103*, 717-724.
- Johnston, M. R.; Carsten, L. D.; Douglas, L.; Sands, D. C. Epidemic development and

- virulence in 1995-1998 of *Puccinia coronata*, a potential biocontrol agent of wild oats on San Clemente Island. *Biological Control* **2000**, *17*, 250-257.
- Jussila, M.; Sontag-Strohm, T.; Ulvinen, O. The identification of Finnish oat cultivars (*Avena sativa* L.) by the use of SDS-PAGE of the avenins in homogenous and gradient gels. *Acta Agric. Scand., Sect. B, Soil and Plant Sci.* **1992**, *42*, 106-110.
- Kempainen, H.; Kirkkari, A.-M. "Viljan kuivaus korkeissa lämpötiloissa [Drying grain at high temperatures]," TTS Institute, 2002.
- Kerckhof, P. J. A. M.; Coumans, W. J. Drying: a fascinating unit operation. *Chemical Engineering Journal* **2002**, *86*, 1-2.
- Kirkkari, A.-M.; Peltonen-Sainio, P.; Lehtinen, P. Dehulling capacity and storability of naked oat. *Agricultural and Food Science* **2004**, *13*, 198-211.
- Kunze, O. R. Effect of drying on grain quality- Moisture readsorption causes fissured grains. *Cereal Foods World* **2001**, *46*, 16-19.
- Labuza, T. P.; Kaanane, A.; Chen, J. Y. Effect of temperature on the moisture sorption isotherms and water activity shift of two dehydrated foods. *J. Food Sci.* **1985**, *50*, 385-391.
- Lacey, J.; Magan, N. Fungi in cereal grains: their occurrence and water and temperature relationships. In *Cereal grain: Mycotoxins, fungi and quality in drying and storage* Vol. J. Chelkowski, Ed.; Elsevier Science Publishers B.V.: Amsterdam, 1991.
- Lapveteläinen, A.; Alho-Lehto, P.; Sinn, L.; Laukkanen, T.; Lindman, T.; Kallio, H.; Kaitaranta, J.; Katajisto, J. Relationship of selected physical, chemical, and sensory parameters in oat grain, rolled oats and cooked oatmeal- a three year study with eight cultivars. *Cereal Chem.* **2001**, *78*, 322-329.
- Lapveteläinen, A.; Rannikko, H. Quantitative sensory profiling of cooked oatmeal. *Lebensm.-Wiss. u.-Technol.* **2000**, *33*, 347-379.
- Lehtinen, P.; Kiiliainen, K.; Lehtomaki, I.; Laakso, S. Effect of heat treatment on lipid stability in processed oats. *J. Cereal Sci.* **2003**, *37*, 215-221.
- Lehtinen, P.; Laakso, S. Role of lipid reactions in quality of oat products. *Agricultural and Food Science* **2004**, *13*, 88-99.
- Leonard, K. J. Regional frequencies of virulence in crown oat rust in the United States from 1990 through 2000. *Plant Dis.* **2000**, *87*, 1301-1310.
- Levine, L. Musing on the mechanics of flaking rolls. *Cereal Foods World* **1993**, *38*, 873-874.
- Levine, L.; Campanella, O.; Corvalan, C.; Okos, M. A model for predicting forces and work inputs in cereal flaking. *Cereal Foods World* **2004a**, *49*, 11-19.
- Levine, L.; Campanella, O.; Okos, M. R.; Ross, K. Observations of the physicochemical changes with flaking. *Cereal Foods World* **2004b**, *49*, 65-70.
- Levine, L.; Campanella, O. H.; Corvalan, C. M.; Okos, M. R.; Gonzalez, D. A model for predicting the aspect ratio of cereal flakes. *Cereal Foods World* **2003**, *48*, 289.
- Levine, L.; Corvalan, C. M.; Campanella, O.; Okos, M. R. A model describing the two-dimensional calendaring of finite width sheets. *Chemical Engineering Science* **2002**, *57*, 643-650.
- Levine, L.; Levine, S. A preliminary investigation of the deformation of cereal pellets by flaking rolls. *Cereal Foods World* **1997**, *42*, 445-451.
- Lookhart, G.; Albers, L.; Pomeranz, Y. The effect of commercial processing on some chemical and physical properties of oat groats. *Cereal Chem.* **1986**, *63*, 280-282.
- Machado, M. d. F.; Oliveira, F. A. R. Kinetics of moisture uptake and soluble-solids loss by

- puffed breakfast cereals immersed in water. *International Journal of Food Science & Technology* **1998**, 33, 225-238.
- Majumdar, S.; Jayas, D. S. Classification of cereal grains using machine vision: I. Morphology models. *Trans. ASAE* **2000**, 43, 1669-1675.
- Marzec, A.; Lewicki, P. P. Antiplasticization of cereal-based products by water. Part I. Extruded flat bread. *J. Food Eng.* **2006**, 73, 1-8.
- McCabe, W. L.; Smith, J. C. *Unit operations of chemical engineering*, 2nd edition ed.; McGraw-Hill Book Co.: New York, 1967; 1007.
- McMinn, W. A. M.; McKee, D. J.; Magee, R. A. Moisture adsorption behaviour of oat meal biscuits and oat flakes. *J. Food Eng.* **2007**, 79, 481-493.
- McDonough, C. M.; Anderson, B. J.; Rooney, L. W. Structural characteristics of steam-flaked sorghum. *Cereal Chem.* **1997**, 74, 542-547.
- Molteberg, E. L.; Solheim, R.; Dimberg, L. H.; Frølich, W. Variation in oat groats due to variety, storage and heat-treatment II: Sensory quality. *J. Cereal Sci.* **1996**, 24, 273-282.
- Multon, J. L. Spoilage mechanisms of grains and seeds in post-harvest ecosystem, the resulting losses and strategies for the defence of stocks. In *Preservation and storage of grains, seeds and their by-products* Vol. J. L. Multon, Ed.; Lavoisier Publishing Inc.: New York, 1988.
- Oeding, J. Einfluß der hydrothermischen Behandlung und des Flockierens auf die funktionellen und die physikalischen Eigenschaften von Haferflocke. Doctoral dissertation, University of Hohenheim, 1996.
- Oomah, B. D. Characteristics of commercially heat-treated oat groats. *Int. J. Food Sci. Technol.* **1987**, 22, 299-308.
- Parde, S. R.; Jayas, D. S.; White, N. D. G. Grain drying: a review. *Sciences des aliments* **2003**, 23, 589-622.
- Paton, D. Oat starch. Part 1. Extraction, purification and pasting properties. *Die Stärke* **1977**, 29, 149-153.
- Peleg, M. Mapping the stiffness-temperature-moisture relationship of solid biomaterials at and around their glass transition. *Rheol. Acta* **1993**, 32, 575-580.
- Peleg, M. A mathematical model of crunchiness/crispness loss in breakfast cereals. *J. Texture Stud.* **1994**, 25, 403-410.
- Peltonen-Sainio, P.; Kirkkari, A.-M.; Jauhiainen, L. Characterising strengths, weaknesses, opportunities and threats in producing naked oats as a novel crop for northern growing conditions. *Agricultural and Food Science* **2004a**, 13, 212-228.
- Peltonen-Sainio, P.; Lehtinen, P.; Kontturi, M.; Rajala, A.; Kirkkari, A.-M. Impact hulling of oat grain to improve quality of on-farm produced feed 2. Groat breakage and storability. *Agricultural and Food Science* **2004b**, 13, 29-38.
- Peltonen-Sainio, P.; Muurinen, S.; Vilppu, M.; Rajala, A.; Gates, F.; Kirkkari, A.-M. Germination and grain vigour of naked oat in response to grain moisture at harvest. *J. Agric. Sci.* **2001**, 137, 147-156.
- Peterson, D. M. Oat antioxidants. *J. Cereal Sci.* **2001**, 33, 115-129.
- Pomeranz, Y. Biochemical, functional and nutritive changes during storage. In *Storage of Cereal Grains and Their Products* Vol. C. M. Christensen, Ed.; American Association of Cereal Chemists: St. Paul, MN., 1982.
- Pullinen, T. "Global oats market assessment," Ministry of Agriculture and Forestry, 1998.
- Ray, A.; Shenoy, A. V. PVC calendaring: a simplified prediction technique. *Journal of*

- Applied Polymer Science* **1985**, *30*, 1-18.
- Regulation (EC) No 178/2002 of the European Parliament and of the council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety.;, 2002.
- Rhymer, C.; Ames, N.; Malcolmson, L.; Brown, D.; Duguid, S. Effects of genotype and environment on the starch properties and end-product quality of oats. *Cereal Chem.* **2005**, *82*, 197-203.
- Rodal, J. J. A. Exploring volume change, angular distortion in a calendering nip. *Paper and Pulp* **1993**, *67*, 47-54.
- Roos, Y. H. *Phase transitions in foods*; Academic Press Inc.: San Diego, California, 1995.
- Roos, Y. H.; Roininen, K.; Jouppila, K.; Tuorila, H. Glass transition and water plasticization effects on crispness of a snack food extrudate. *Int. J. Food Prop.* **1998**, *1*, 163-180.
- Saastamoinen, M.; Hietaniemi, V.; Pihlava, J.-M.; Euroala, M.; Kontturi, M.; Tuuri, H.; Niskanen, M.; Kangas, A. Beta-glucan contents of groats of different oat cultivars in official variety, in organic cultivation, and in nitrogen fertilization trials in Finland. *Agricultural and Food Science* **2004**, *13*, 68-79.
- Saastamoinen, M.; Plaami, S.; Kumpulainen, J. Genetic and environmental variation in beta-glucan content of oats cultivated or tested in Finland. *J. Cereal Sci.* **1992**, *16*, 279-290.
- Sacchetti, G.; Pittia, P.; Biserni, M.; Pinnavaia, G. G.; Rosa, M. D. Kinetic modelling of textural changes in ready-to-eat breakfast cereals during soaking in semi-skimmed milk. *Int J Food Sci Tech* **2003**, *38*, 135-143.
- Sahasrabudhe, M. R. Measurement of lipase activity in single grains of oat (*Avena sativa* L.). *JAOCs* **1982**, *59*, 354-355.
- Salmenkallio-Marttila, M.; Heiniö, R.-L.; Myllymäki, O.; Lille, M.; Autio, K.; K., P. Relating microstructure, sensory and instrumental texture of processed oat. *Agricultural and Food Science* **2004**, *13*, 124-137.
- Salovaara, H. Oats in food processes. *The 25th Nordic Cereal Congress. The Nordic Cereal Industry in an Integrating Europe, Helsinki*; Helsinki University Press, 1993; pp 133-138.
- Sapru, V.; Labuza, T. Moisture transfer simulation in packaged cereal-fruit systems. *J. Food Eng.* **1996**, *27*, 45-61.
- Sides, A.; Robards, K.; Helliwell, S.; An, M. Changes in the volatile profile of oats induced by processing. *Journal of Agricultural and Food Chemistry* **2001**, *49*, 2125-2130.
- Strange, E. D.; Onwulata, C. I. Effect of particle size on the water sorption properties of cereal fibers. *Journal of food quality* **2000**, *25*, 63-73.
- Sun, W. Q. Glassy state and seed storage stability: The WLF kinetics of seed viability loss at $T > T_g$ and the plasticization effect of water on storage stability. *Ann. Bot.* **1997**, *79*, 291-297.
- Symons, S. J.; Fulcher, R. G. Determination of variation in oat kernel morphology by digital image analysis. *J. Cereal Sci.* **1988a**, *7*, 219-228.
- Symons, S. J.; Fulcher, R. G. Relationship between oat kernel weight and milling yield. *J. Cereal Sci.* **1988b**, *7*, 215-217.
- Throne, J. E.; Doehlert, D. C.; McMullen, M. S. Susceptibility of commercial oat cultivars to *Cryptolestes pusillus* and *Oryzaphilus surinamensis*. *Journal of Stored*

- Products Research* **2003**, 39, 213-223.
- Vorwerck, K. Hydrothermische Behandlung von Hafer. *Getreide Mehl Brot* **1988**, 42, 199-202.
- Webster, F. H. Whole-grain oats and oat products. In *Whole-grain foods in health and disease* Vol. L. Marquart; o. L. Slavin and R. G. Fulcher, Eds.; American Association of Cereal Chemists: St. Paul, MN., 2002.
- Welch, R. W.; Leggett, J. M.; Lloyd, J. D. Variation in the kernel (1-3)(1-4)-beta-D-glucan content of oat cultivars and wild *Avena* species and its relationship to other characteristics. *J. Cereal Sci.* **1991**, 13, 173-178.
- Welch, R. W.; Lloyd, J. D. Kernel (1-3)(1-4)-beta-D-glucan content of oat genotypes. *J. Cereal Sci.* **1989**, 9, 35-40.
- White, E. M. Structure and development of oats. In *The Oat Crop* Vol. R. W. Welch, Ed.; Chapman and Hall: London, 1995.
- White, N. D. G.; Hulasare, R. B.; Jayas, D. S. Effects of storage conditions on quality loss of hull-less and hulled oats and barley. *Can. J. Plant Sci.* **1999**, 79, 475-482.
- Wikström Jansson, K.; Lindahl, L. Rheological changes in oatmeal suspensions during heat treatment. *J. Food Sci.* **1991**, 56, 1685-1689.
- Williams, R. J. Methods for determination of glass transitions in seeds. *Ann. Bot.* **1994**, 74, 525-530.
- Youngs, V. L.; Peterson, D. M.; Brown, C. M. Oats. In *Advances in Cereal Science and Technology* Vol. 5; American Association of Cereal Chemists: St. Paul, MN., 1982; pp 49-105.
- Zhang, D.; Doehlert, D. C.; Moore, W. R. Factors affecting viscosity of slurries of oat groat flours. *Cereal Chem.* **1997**, 74, 722-726.
- Zhang, D.; Doehlert, D. C.; Moore, W. R. Rheological properties of (1→3)(1→4)-β-D-glucan from raw, roasted and steamed oat groats. *Cereal Chem.* **1998**, 75, 433-438.
- Zhou, M.; Glennie-Holmes, M.; Robards, K.; Helliwell, S. Effects of processing and short-time storage on the pasting characteristics of slurries made from raw and rolled oats. *Food Australia* **1999**, 51, 251-258.
- Zhou, M.; Robards, K.; Glennie-Holmes, M.; Helliwell, S. Contribution of volatiles to the flavour of oatmeal. *J. Sci. Food Agric.* **2000a**, 80, 247-254.
- Zhou, M.; Robards, K.; Glennie-Holmes, M.; Helliwell, S. Effects of enzyme treatment and processing on pasting and thermal properties of oats. *J. Sci. Food Agric.* **2000b**, 80, 1486-1494.