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Review paper
PARTICLE CHARACTERISTICS OF FLAKE-CUT MEAT

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Abstract

The size of flake-cut meat is an important quality determinant of comminuted meat products which, potentially, depends upon a large number of factors. Temperature and whether or not the meat is pre-broken have a major influence on the resulting particle size distribution, as does aperture size. Meat flaked at -7°C produced two to three times more flakes than at -3°C. Under some conditions the particles produced were as little as 0.4 mm thick and characteristically were thicker at one end.

High speed photography, used to visualise the cutting action, indicated that size reduction occurs in a controlled manner providing that the meat is neither too cold, nor too warm. Above -1°C the meat merely deforms rather than being cut.

Single, discrete particles, examined using scanning electron microscopy (SEM) and cryo-SEM, unexpectedly did not exhibit the usual features of cleanly-cut meat. The lack of ultrastructural detail was attributed to a smearing of sarcoplasmic fluid produced by a localised, transient rise in temperature during flaking.

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Introduction

Consumer demand for conveniently sized, easy-to-cook, no-waste portions of consistent quality, coupled with the need to utilise the lower quality cuts of the carcass, has led to a proliferation of comminuted meat products. One of the primary reasons for comminuting is to overcome the connective tissue toughness associated with many of these lower quality cuts. Consequently, one of the most important quality determinants is particle size, which, with associated characteristics of the particles such as shape and surface morphology, determines not only the subjective perception of particle size (Berry & Civille, 1986) but also influences the physical appearance of the product (Durland *et al.*, 1982) and the adhesion between particles (Acton, 1972).

Flaking is probably the most recent method of comminution. A commonly used flaking system, introduced in the 1970's by the American company, Urschel Laboratories, is now widely used in the manufacture of grillsteaks and other restructured meat products. Unlike bowl chopping or mincing, the technique produces discrete particles (provided the meat is cold enough), which are amenable to particle size analysis and investigations of the surface characteristics of the particle.

As well as reporting upon the surface microstructure of the particles and factors influencing the size distribution of flake-cut meat, this paper is also concerned with understanding how size reduction is achieved - information which is invaluable for the development and control of new and existing products.

UK-style grillsteaks

The scheme on the right of Figure 1 shows the typical sequence of operations involved in the manufacture of grillsteaks in the UK. Meat is usually purchased as frozen blocks (typically up to 30 kg), which need to be tempered.

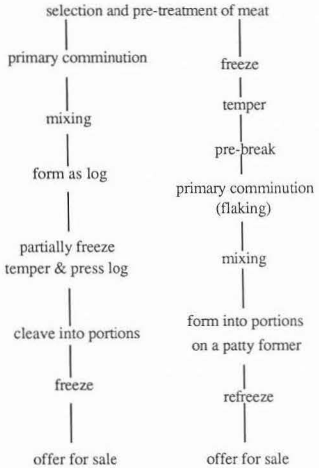

Fig. 1. Two common methods of manufacture of restructured meat products. The sequence of operations on the right is followed by most UK manufacturers; the scheme on the left has been followed by most of the literature on the subject.

usually between -1°C and -8°C, to facilitate subsequent processing. The required size reduction is normally achieved in two stages - a relatively coarse comminution procedure, pre-breaking, followed by a comparatively fine comminution procedure, flaking. Sodium chloride, either as crystals or as a solution, is added during mixing, together with any herbs, spices or other non-meat ingredients. Good adhesion between meat pieces in the cooked product is normally attributed to proteins solubilized and extracted during this procedure. The most popular means of imparting shape to the resulting sticky mass is via a high speed patty former.

The scheme on the left of Figure 1 is typical of most of the literature on the subject. In commercial practice in the U.S., however, the meat is usually hydro-flaked in the frozen state and then thawed or tempered to ≤+4°C before being flaked (Berkowitz, personal comm.). Alternatively the frozen meat may be thawed to about +2°C and then flaked. There is, therefore, an important difference between this and common practice in the UK, where the meat is usually flaked in a semi-frozen condition. As in the UK, patty forming machines are used by most manufacturers of restructured meat products, though some small processors will form the finished product as a log - a practice declining because of cost considerations.

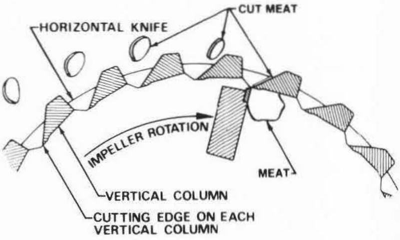

Fig. 2. Schematic diagram illustrating the cutting principle of the Comitrol® processor by Urschel Laboratories.

Products made for the USA market, usually referred to as restructured steaks, tend to be sold to hotels, restaurants and institutional establishments, rather than through retail outlets as in the United Kingdom.

Our studies have concentrated on meat flaked below the initial freezing point (ifp) as this is more relevant to UK manufacturers.

Flaking using the Comitrol processor

Meat is cut by impelling it at high speed, typically 3,000 rpm in the UK, or 3,600 rpm in the USA, against a stationary cutting head (Figure 2).

There are a large variety of cutting heads available, differing in the number of cutting stations and the aperture size (i.e. opening size) (Figure 3). Providing that the meat is hard enough, typically 2°C or 3°C below the initial freezing point of meat (about -1°C), discrete pieces are produced; the appearance of meat flaked above the ifp is quite different, superficially resembling meat which has been ground (Jolley & Purslow, 1988), as shown in Figure 4. The temperature at which there is a transition from the production of discrete flakes to that of mince-like strands depends upon aperture size. Mince-like strands may be produced at several degrees below freezing, if the aperture size is too small. We have observed strands from meat flaked through a 1.5 mm aperture at a temperature of about -4°C.

Measuring particle size in comminuted meat products

There are many situations where size measurements are desirable. Consequently, a wide range of particle sizing techniques have been developed over the last twenty years or so, particularly for measurements in the sub-micron range, where current interest is keenest. However, despite the relatively large

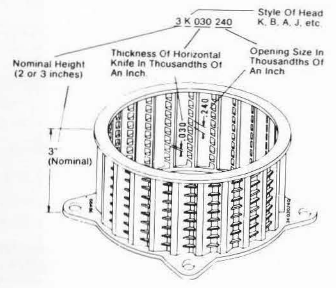

Fig. 3. Diagram showing the design of the cutting head of the Comitrol® processor and its characteristic dimensions.

Fig. 4. Photograph showing appearance of meat flaked through an aperture size of 4.6 mm at a temperature of about -1°C.

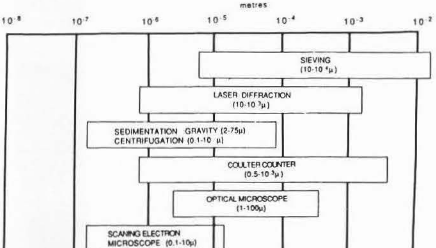

Fig. 5. Particle size range for some common methods of measuring particle size.

number of techniques available (Fig. 5), and the universal recognition of the need to measure particle size in comminuted meat products, relatively few studies of particle size in relation to meat comminution have been reported.

One exception to this generalization is the work of Girard *et al.* (1985) who used a Coulter Counter® to show the change in the size distribution of bowl chopped meat during comminution for up to 40 minutes. Particles ranged in size from 1 to 30 microns, and since the diameter of a muscle fibre is typically about 50 microns (Light *et al.*, 1985), this implies that tissue disruption must have been quite extensive. However, the technique requires the sample to be highly diluted, which could cause further tissue breakdown.

Various microscopical techniques have been used in size analysis, but, in order to give statistically significant data many individual particles need to be measured, with the result that manual procedures are generally slow and labour intensive. These disadvantages have largely been overcome with the advent of automated image analysis techniques. The more sophisticated of these machines can perform projected area measurements and measure statistical diameters such as the commonly used Ferêt and Martin diameters. Holes can be recognised and routine shape analysis performed. Images may be stored, together with derived data, which may be presented numerically or graphically.

Automated image analysis has been used for example to measure the fat to lean ratio in boneless fresh, or cured, meats (Newman, 1984) and minced meat (Newman, 1987), and also for quantifying the amount of collagen, elastin and bone in histological sections of meat (Hildebrandt & Hirst, 1985).

Thus the technique applies equally well to images produced by scanning electron or transmission electron microscopes and direct images of larger objects.

Factors potentially affecting particle size

Using a video image analysis (VIA) technique we have investigated some of the large number of factors which may determine particle size. Our results to date are summarised in Table 1 (Sheard *et al.*, 1989, 1990; Sheard *et al.*, unpublished data).

Of the factors listed under the heading "Machine Parameters" there are four which are pre-selected by the user (aperture size, number of cutting stations, impeller speed and impeller design). In a recent study we made size measurements of meat flaked at speeds of 3,360 and 6,680 rpm through aperture sizes of 1.5, 6.1 and 19.0 mm using two different types of impeller. At least two flake heads, differing in the number of cutting stations, were examined for each aperture size. Aperture size was the most important determinant of particle

Table 1. Factors potentially affecting the particle size of flaked meat.

Machine parameters	**Comments**
1. Aperture size.	Correlates with particle diameter; also affects particle thickness.
2. Number of cutting stations.	Probably affects particle thickness.
3. Impeller speed (3,000 - 7,000 rpm)	Probably not important.
4. Impeller design.	Affects machine operation (noise, flake head wear) but probably not critical for particle size.
5. Flake head wear.	Less efficient cutting; increased heat gain.
6. Feed rate.	No published data.
Properties of meat raw materials	
1. Temperature of meat.	Meat flaked at low temperatures produces particles which are thinner and have a greater overall surface area. Mince-like strands are produced if the meat is too warm.
2. Input piece size; pre-breaking.	Input piece size limits maximum size obtainable; meat pre-broken by grinding breaks up easily.
3. Meat species.	Small differences observed between lean beef, turkey breast and turkey thigh.
4. Type of muscle.	No published data.
5. Other factors e.g. animal age, PSE and DFD meat, post-mortem history, freezing rate.	No published data.

size, influencing the size distribution of particles, the number of particles per gram of sample, the resulting surface area per gram of sample, the mean particle diameter and also the mean thickness of flakes. There was little effect on particle size of impeller speed or the design of the impeller. For a given aperture size and temperature, the mean particle thickness was also dependent upon the number of cutting stations, more cutting stations giving rise to slightly thinner particles.

As with any other comminution system the cutting surfaces of the machine become worn over a period of time, particularly if the meat is flaked at temperatures well below the initial freezing point or if the material contains a high proportion of gristle, or bone. We have observed that, for given conditions, a damaged flake head, as shown in Figure 6, tended to produce mince-like strands at a slightly lower temperature than a new head. Also there was a greater amount of residual material left on the inner surface of the head after flaking for approximately the same period of time. Analysis of this residue showed a slightly higher connective tissue content than that of the original raw material, suggesting that some connective tissue had been stripped out during flaking and implying some destruction of structure rather than clean cutting.

Of the factors investigated to date the two most important properties of the raw material are temperature and whether or not it has been pre-broken. The practical consequences of using meat which is either too cold or too warm have been summarised by Bezanson

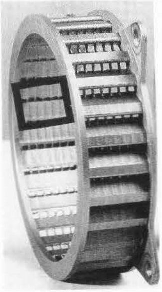

Fig. 6. Photograph showing a small area (bottom) on the inside surface of a damaged flaking head (left). The opening is divided into seven apertures, each of 4.6 mm. Note that the pitted appearance of the cutting surface indicates that the head has been worn beyond repair.

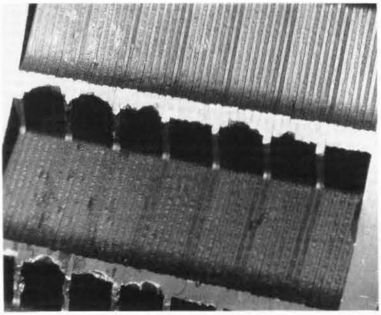

Table 2. Means (± standard deviation) of number and thickness of particles for meat flaked through aperture sizes of 6.1, 9.9 and 19.0 mm at -3°C, with and without pre-breaking, and -7°C.

	number of particles per gram			thickness (mm)		
aperture size (mm)	-3°C (pre-broken)	-7°C (pre-broken)	-3°C (not pre-broken[1])	-3°C (pre-broken)	-7°C (pre-broken)	-3°C (not pre-broken[1])
6.1	164 ± 29	368 ± 37	37 ± 9	1.08 ± 0.19	0.43 ± 0.03	1.21 ± 0.28
9.9	61 ± 13	148 ± 29	17 ± 1	1.52 ± 0.05	0.63 ± 0.13	1.72 ± 0.16
19.0	30 ± 3	108 ± 6	7 ± 1	1.55 ± 0.20	0.80 ± 0.07	1.52 ± 0.06

[1] meat introduced to the machine as bandsawn sticks approximately 15 x 3.5 x 3.5 cm.

(1975) and demonstrated in semi-quantitative fashion by Ellery (1985). Pre-breaking hard frozen meat produces excessive fines, is detrimental to product cohesion and can cause equipment failure.

Table 2 shows the effects of the temperature of the meat and pre-breaking on the size of particles obtained from the flaking operation (Sheard *et al.*, 1990). Pre-broken particles ranged in size from tiny fragments of less than 1 mm in diameter to large, irregularly-shaped pieces approximately 4-5 cm in diameter. For a given aperture size, meat which had been pre-broken at -7°C then flaked at -7°C had two to three times the number of particles per gram compared with meat which had been pre-broken at -3°C and then flaked at -3°C. Furthermore, at -3°C, far fewer particles were produced where the meat had not been previously pre-broken. Particle thickness was also highly dependent upon temperature, but dependent upon aperture size to a lesser extent. At a given aperture size, particles produced by flaking at -7°C were about half as thick as those flaked at -3°C.

These results have important implications for the textural quality of restructured meat products. For many particles, it is likely that the fibres are cut obliquely, but let us consider the two limiting cases, where the fibres run parallel, or at 90 degrees, to the long axis of the flake. In the first case, some flakes may be as little as 8 fibres thick (i.e. 0.4 mm, assuming a fibre diameter of 50 microns); whilst in the second case, fibres may be only 0.4 mm long. Since restructured products are required to simulate the eating quality of whole muscle steak (where steaks are typically cut transversely to the fibre direction, to give a thickness of 1-2 cm), many fail to meet this objective because the constituent particles are too small to confer sufficient fibre character.

In broad terms the effect of temperature can be explained on the basis of the mechanical properties of the meat, which becomes more brittle with decreasing temperature (Munro, 1983). The change in mechanical properties with temperature could simply be due to the ice content of the meat at a given temperature. To investigate the relationship between temperature and particle size, measurements were made of the number and thickness of particles for diced meat (19 mm cubes) flaked, without being pre-broken, through an aperture size of 12.9 mm at 1°C intervals between -2 and -7°C (Fig. 7). The relationship between ice content and temperature in this range is highly non-linear. The number of particles per gram of sample increased from about 40 at -2°C to 80 particles/g at -4.5°C. Between -4.5°C and -7°C, the number of particles increased from about 80 to 140 particles/g. The ice contents at -2 and -4.5°C are 48% and 73%, respectively and 78% at -7°C (Morley, 1972). The mean particle thickness decreased from about 1.4 mm at -2 to 0.8 mm at -4.5°C and to 0.5 mm at -7°C. The surface area, which is inversely related to the thickness, ranged from 2,100 mm^2/g at -7°C to 780 mm^2/g at -2°C. It is extremely doubtful that a change in ice content of just 5% would account for these marked changes in particle size between -4.5°C and -7°C. The data appear, therefore, to substantiate our earlier suggestion that factors other than ice content - such as the increased viscosity of the unfrozen liquor and the dehydration of the fibres - determine the size of comminuted meat (Sheard *et al.*, 1989).

Flaking single pieces of meat

In the discussion which follows we use the term 'cutting', though flaking need not necessarily involve a true cutting action. A crack, for example, could be initiated by impact at the surface and could propagate through a piece of meat without the cutting edge traversing the width of the piece. Fracture might occur, therefore, by a combination of impact, cutting and other mechanisms. The term is used here because, visually, the

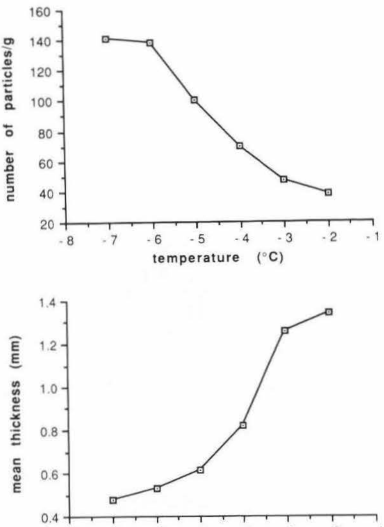

Fig. 7. Effect of flake temperature on the number of particles per gram of sample and the mean thickness of particles.

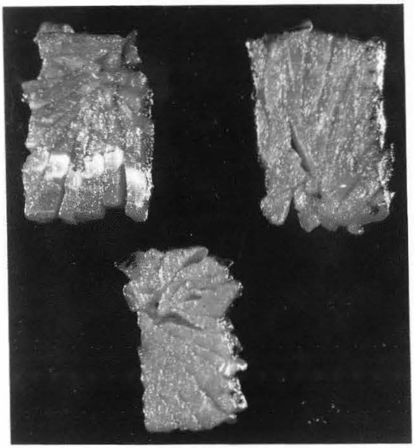

Fig. 8. Photograph showing single pieces of meat flaked through a 40.6 mm aperture and reconstructed. Each piece measured 3x2x0.5 cm originally and the fibre direction was different in each case. The pieces were cut cleanly in a radial fashion giving rise to a number of differently sized wedge-shaped pieces.

surfaces created resemble those of cleanly-cut meat or meat that has fractured in a brittle fashion. Such surfaces are usually smooth and when placed in juxtaposition, generally fit back together again quite readily. In meat which is not cut cleanly, or meat which exhibits viscoelastic fracture behaviour, distended and twisted strands of connective tissue and groups of fibres can be seen protruding from a relatively rough, uneven surface (Dobraszczyk *et al.*, 1987).

Figure 8 illustrates how a single piece of meat (approximately 3 x 2 x 0.5 cm) is cut. Each piece was flaked individually at about -3°C through an aperture size of 40.6 mm. The resultant flake-cut pieces were collected and the original piece reconstructed. It can be seen that in each case the piece has been cut in a radial fashion regardless of fibre direction, giving rise to a number of wedge-shaped pieces, each having a thick end and a thin end. Each piece was cut in a similar way, regardless of fibre direction and the presence or absence of fat, as would occur with a true cutting action.

Meat deforms less readily against the cutting head at low temperatures (Anon., 1980). Consequently the depth of cut is reduced producing thinner particles, as indicated in Figure 7. However, meat at low temperatures ($\leq$-3°C) is also more brittle and 'cutting' could be accompanied by multiple cracking, which might also account for the greater number of particles observed at reduced temperatures (Table 2).

High speed photography has played a crucial role in design modifications to the impeller (Koberna, personal communication). Figure 9 shows three different types of impeller. The first generation of impellers were straight-bladed, which, because of their noisy operation were superceded by impellers whose blades either sloped backwards or forwards (Fig. 9A). At high feed rates, however, meat could rub against non-cutting surfaces causing an unnecessary rise in temperature. This particular problem was overcome by using a dog-leg impeller (Fig. 9B); but this had the disadvantage that excessive wear occurred in a relatively small area of the flaking head. The latest generation of impellers, the dio-cut impeller (Fig. 9C), have a ring of alternately forward and backward sloping blades which moves the meat across the entire length of the cutting head thus minimising wear, without the disadvantages incurred with previous impeller designs.

We have used high speed photography to show how the cutting action depends upon aperture size, temperature and whether or not the meat has previously been pre-broken. A single piece of meat (approximately 3 x 2 x 0.5 cm), flaked through an aperture size of 40.6 mm at a temperature of about -3°C, was reduced to flakes in about a third of a revolution (i.e. 0.006 s); however, several revolutions (0.14 s or more) were required to cut a piece of the same size using a 4.6 mm aperture. In this case, pieces of meat remained intact to the point of being cut by the sharpened surfaces of the flaking head. Meat which had previously been pre-broken by grinding, however, tended to deform, or even break up, on impact with the impeller.

The period of time required to reduce a piece of meat to flakes also depends upon temperature. Attempts to gauge the time required to "cut" an individual piece of meat at -1°C, however, were impracticable because of the difficulty in distinguishing one piece from subsequent pieces falling into the cutting head. However, for a given aperture size, the overall cutting time may well be ten times or more at flake temperatures above the initial freezing point compared with lower temperatures (≤-3°C) where discrete flakes are produced. Above the ifp, rather than being cut cleanly, the meat is deformed as it is forced against the flaking head, becoming smeared around the inside surface by the impeller.

The time required for cutting is indicative of the type of fracture behaviour. Under some conditions, several hundred flakes may be produced from a piece of meat of the size observed using high speed photography and, thus, to make a single cut (i.e. to propagate a single crack) across the face of the specimen, must take place more rapidly than the overall cutting time. Munro (1983) has shown that under brittle conditions, crack propagation in meat, over a distance of about 10 mm, takes less than 0.02 s; under viscoelastic conditions, fracture occurs more slowly, over 2-3 s. Regardless of the temperature of the meat, the rotational speed of the impeller is constant. Thus, for a flaking head having twenty cutting stations, the average time required to traverse a single cutting station is 0.001 s, which is far too short to allow for crack propagation under viscoelastic conditions. Consequently, the meat merely deforms, rather than being cut cleanly, as occurs at lower temperatures when the meat is brittle.

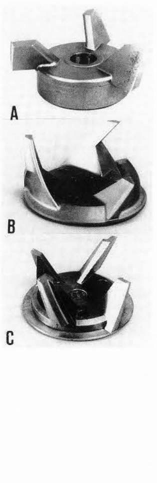

Fig. 9. Photograph illustrating three different designs of impeller. A) Impeller with 3 backward sloping blades. Pieces of meat slide away from the base of the impeller and are cut at the trailing edge. B) Dog-leg impeller. Meat is cut in the V-shaped pocket. C) Dio-cut impeller having alternately forward and backward sloping blades. The backward sloping blades are shortened so that the meat slides away from the base and into the path of the forward sloping blade behind it.

Ultrastructure of single flakes

Great advances have been made, particularly over the last 20 years, in elucidating the hierarchical structure of muscle and the ultrastructure of muscle fibres subject to a variety of pre- and post-rigor treatments. These morphological features have been described and reviewed by many authors (Voyle, 1979, 1981; Offer & Trinick, 1983; Lewis *et al.*, 1986). Microscopical analyses have also been used to show the location, appearance and structure of the major components in a wide range of meat products (Lewis, 1979; Theno *et al.*, 1978; Voyle *et al.*, 1986). Many studies have been undertaken on a variety of comminuted meat products to resolve whether or not the matrix could be accurately described as a true meat emulsion (Swasdee *et al.*, 1982; Foegeding, 1989; Regenstein, 1989). However, there have been few microscopical studies undertaken on restructured meat products, and the studies that have been made have concentrated on the finished product, either frozen (Nusbaum *et al.*, 1983; Bernal & Stanley, 1986) or cooked (Cardello *et al.*, 1983; Bernal & Stanley, 1986), rather than the morphology of individual flake-cut pieces.

Cardello *et al.* (1983), who examined products, after cooking, made from meat flaked through aperture sizes of 1.5, 19.0 and 40.1 mm suggested that fibres (even those of meat flaked through a 1.5 mm aperture) appeared similar to "normal" cooked whole muscle tissue. Bernal and Stanley (1986) commented that there was evidence of "a damaged fibrous structure" in the cooked product. They did not report the conditions under which the product was made, however. Nusbaum *et al.* (1983) were interested primarily in the effects of freezing rate on the microstructure of the product and, in particular, its relationship with quality and cooking losses. These workers suggest a mechanism to explain why slowly frozen products, with large ice crystal cavities, should have greater cooking losses.

Unfortunately, the processing conditions

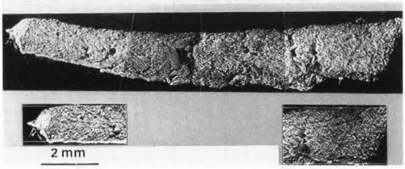

Fig. 10. Edge view of a single flake of turkey breast flaked through an aperture size of 4.6 mm at -3°C, showing the characteristic wedge shape of particles, and their typical thickness. The upper view has been constructed from 4 separate electron micrographs; the two lower views show the ends of the flake. The thick and thin ends measure 1.88 mm and 1.19 mm, respectively. The overall length of the flake is about 12 mm. Notice also the alignment of surface material from right to left, suggesting that cutting begins at the thick end.

were not sufficiently similar, or well documented, to make comparisons between the three studies, or to draw any definite conclusions.

Figure 10 is an edge view of a single flake at low power magnification, illustrating the typical wedge shape apparent in many flakes. The width of the thick and thin ends, obtained using the caliper facility on the microscope, were 1.88 and 1.19 mm, respectively. These are the kind of values we expect from our VIA results. There also appears to be some orientation of surface material from right to left, suggesting that cutting begins at the thick end of the flake, an observation confirmed by examination of a large number of flakes. This finding, together with the result that individual pieces appear to be cut in a radial fashion (Fig. 8), suggests that individual cuts made on a single piece of meat terminate, rather than begin, at the focus. The cuts are presumably made in a sequential fashion.

Flakes were collected immediately after flaking, fixed in glutaraldehyde, dehydrated, critical point dried and sputter coated with gold. Certain characteristic features were observed in material prepared in this way. Ice crystal cavities were obvious; these ranged in size from about 25 to 75 microns; fibre direction was also obvious in most flakes (there did not appear to be any preferential fibre direction in those flakes which were examined). In some flakes, individual fibres could be seen, as could strands of perimysial connective tissue. However, the most striking feature was the lack of fine structure normally associated with cleanly-cut meat at magnifications up to 650 times.

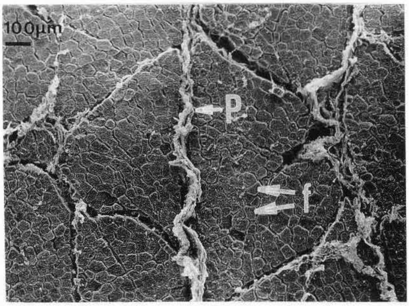

Fig. 11. SEM micrograph of scalpel-cut beef sternomandibularis. The clearly defined fibres (f) are delineated by endomysial connective tissue, which is not easily discernible on this section, at this magnification. The fibres are themselves arranged into fibre bundles, surrounded by perimysial connective tissue (P).

Figure 11 is a micrograph of meat cut perpendicular to the fibre direction with a sharp scalpel, examined at a magnification of 80 times. It illustrates the well-known morphological features of meat structure, viz, individual fibres organised into fibre bundles. Endomysial and perimysial connective tissue can be seen surrounding individual fibres and fibre bundles, respectively. Figures 12 and 13 show the typical appearance of the flakes we obtained, cut along (Fig. 12) and across (Fig. 13) the fibres. The flakes were collected and prepared for microscopy as previously described.

The disorganised web of fibrous matter seen on the surface of the specimen in Fig. 12, which obscured the underlying array of meat fibres, could be collagenous material. This interpretation, however, may be ruled out for two reasons. All the flakes were examined at both high and low magnifications, and any thick tracts of connective tissue or large areas of collagenous material would have been evident at lower magnifications. Secondly, of the flakes examined, which included turkey breast, turkey thigh and forequarter beef, none were found which displayed the characteristic fibrous structure of cleanly-cut meat, though in some cases the surface appearance was rather more amorphous than the matted appearance shown in Fig. 12. Fig. 13 differs superficially from Fig. 12 because of the different fibre directions; it also differs in that the surface appearance is more amorphous. More importantly, neither specimen, regardless of fibre direction, exhibited the characteristic detail associated with cleanly-cut meat.

The relatively smooth surface of the

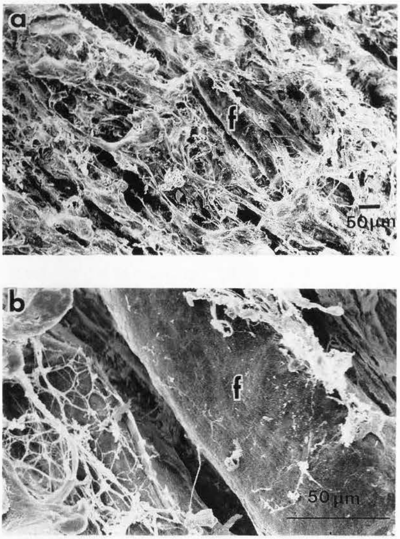

Figure 12 a, b. SEM micrograph of turkey thigh at two different magnifications. The structure (f) is a muscle fibre running parallel to the plane of the surface, with a diameter of about 55 microns. Notice the absence of cross-striations, even at the highest magnification. The nature of the fibrous material which is evident elsewhere is less clear.

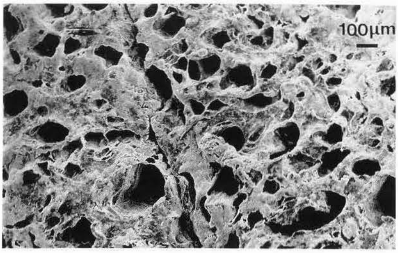

Fig. 13. SEM micrograph of turkey breast flaked through an aperture size of 4.6 mm at -3°C, showing the largely amorphous appearance of the cut surface. Ice crystal cavities range from about 25 to 125 microns, and suggest the fibre direction to be at 90° to the plane of the surface. The fissure, running diagonally across the micrograph, may denote the boundary between fibre bundles or a gap opened up between adjacent fibres.

specimen in Fig. 12, and also the fact that the ends of fibres were not twisted and distorted are also indicative of a clean cutting action. Similar surface characteristics have been observed for specimens that have failed in tension at low temperatures ($\leq$-15°C) and high strain rates, where the meat behaves in a brittle fashion (Dobraszczyk *et al.*, 1987). One would expect a quite different appearance for meat which was not cut cleanly.

The appearance of the flakes could be explained in several ways. It is known that the temperature rises during comminution and some of the ice melts (Ellery, 1985; Sheard *et al.*, 1990), thus making water available for dissolution of already concentrated solutes, which could become deposited on the freshly created surfaces of cut fibres.

Alternatively, the appearance could be due to the denaturation of heat labile proteins. Although the overall rise in temperature of the meat during flaking is only a few degrees, because of the high latent heat of freezing of water, this represents a considerable change in enthalpy, and the transient rise in temperature could be substantially higher, particularly at the surface of a flake, where, presumably, most heating takes place.

Fig. 14 shows the surface of meat cut across the fibres using a bandsaw (Beatty & Jolley, unpublished). Like the flaked material (Fig. 13), the normal muscle structure (Fig. 12) was obscured, and in this instance, some material was evident on the surface, which, conceivably, could be coagulated sarcoplasmic proteins. Since the blade of a bandsaw invariably feels warm to the touch, even when cutting frozen meat, it must reach a temperature of 45-50°C. If the transient rise in temperature during flaking is as large then this could cause the denaturation of heat labile proteins, which might be expected to produce effects similar to those seen in Figures 12 and 13.

A third possible explanation of this surface phenomenon is related to the residue that collects on the inside of the flaking head, small amounts being picked up as the particles emerge from the apertures.

We must also accept the possibility, of course, that these observations were an artefact arising from the preparative procedures. However, by examining flakes using cryo-SEM, where artefacts resulting from fixation, dehydration and critical point drying are avoided, it becomes possible to confirm whether or not these earlier observations were valid.

Figure 15 shows the typical appearance of a specimen examined in this way. The raw material was collected in liquid nitrogen as it

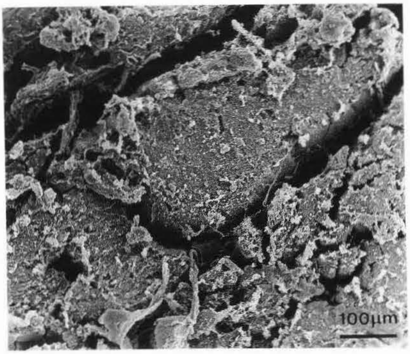

Fig. 14. SEM micrograph of pork Longissimus dorsi cut at about -4°C using a bandsaw. The cut was made perpendicular to the fibre direction at about 130 mm from the anterior end of the muscle. Individual fibres bundles are readily apparent; some individual fibres can be distinguished, but any fine detail is lacking. The micrograph was obtained using a Jeol JSM-35 SEM. Courtesy E.Beatty, University College, Cork.

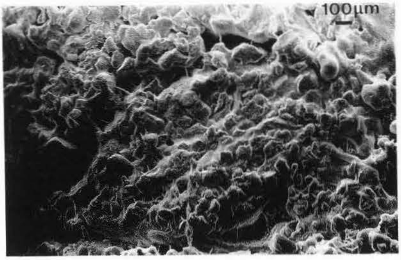

Fig. 15. Cryo-SEM micrograph of beef semitendinosus flaked through an aperture size of 4.6 mm at -2.5°C. The fissure, running from the bottom left hand corner, probably denotes the boundary between fibre bundles. Strands, probably of perimysial connective tissue, can be seen bridging the two surfaces. The general appearance suggests that fibres run at 90° to the plane of the surface.

fell from the flaking head, thus preserving any ice still present. Individual flakes were then transferred to the SEM cold stage whilst still frozen, and then coated with gold and observed as before.

Ice crystal cavities were generally smaller, presumably because of the rapid freezing immediately after flaking, whilst individual fibres were more readily identifiable. Again, specimens had an amorphous appearance, similar to those seen previously, suggesting that the appearance of flakes shown in Figures 12 and 13 are, indeed, genuine observations.

Conclusion

These microscopical observations of individual particles, together with the cine film and VIA results, provide a powerful insight into the mechanism by which semi-frozen meat is cut during flaking. Based upon cine film records and other qualitative observations, individual pieces of meat appear to be cut in a controlled fashion provided that the meat is cold enough to prevent it merely deforming rather than being cut, but not so cold as to cause multiple cracking.

SEM micrographs of these cut surfaces revealed little of the structural detail normally associated with cleanly-cut meat, possibly because it was obscured by a surface smearing of sarcoplasmic fluid. Further characterization of the surface morphology would be of value, as would an examination of the microstructure of material flaked above the ifp. Scanning confocal microscopy, to examine the sub-surface ultrastructure, may prove a useful complementary technique to SEM.

Particle size measurements, made under a wide range of practically relevant conditions, have been made and these will enable the manufacturer to identify which factors are most likely to influence particle size, and by how much. This information is essential not only to reduce variability in product quality arising from differences in particle size, but also in designing the textural quality of new products.

High speed photography provides an invaluable tool in visualising exactly what happens during flaking. The technique could be applied equally well to other systems, not only as a research tool, but also for design purposes and as a diagnostic tool.

The information gained from studies of this type are essential to predict from first principles, rather than trial and error, how changes in the raw material or machine parameters will affect the level of size reduction achieved, and the reasons for variability in response.

Acknowledgments

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We are also grateful to Urschel Laboratories for their co-operation and helpful advice. Figures 2 and 3 are taken with permission from Facts, Flakes & Fabricated Meats. (1980) published by Urschel Labs. Inc., Valparaiso, USA.

Figure 1 is taken with permission from P.D.Jolley & P.P.Purslow (1988) Restructured and reformed meat products: fundamental concepts and new developments. In, Food Structure - Its Creation and Evaluation J.R.Mitchell & J.M.V.Blanshard (eds.). Butterworths, Surrey, England.

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Discussion with Reviewers

J.T.Clayton: Particle size is not adequately defined. Does it mean an overall measure of size (volume)? Or is there one dimension (thickness) that is overriding in importance?

Authors: For all but the simplest shapes, size is, in fact, very difficult to define. A sphere, for example, can be defined by a single dimension - the radius - but this cannot be said of irregularly shaped particles. Many sizing techniques assume that particles are spheres. Moreover different techniques do not necessarily measure the same property of the particle. One would not expect, therefore, VIA to give the same result as a Coulter Counter, for example, which expresses size as the diameter of a sphere having the same volume as the particle.

It would be misleading to suggest that one dimension is of overriding importance. A single flake (i.e. a thin, broad particle) can be conveniently thought of in terms of just two dimensions - its thickness and diameter - but this would not tell us if the projected surface of the particle was circular or rectangular or if its outline was ragged or smooth. One should also remember that comminution will always result in particles of different sizes. The object, therefore, in particle size analysis is usually to arrive at a size distribution which is usually in terms of weight or diameter or some other property depending on the technique being used.

R.A. Segars: How is 'surface area' of the flakes defined, e.g. does surface area times thickness = volume?

P.J. Lillford: The authors mention that the particles are often wedge shaped. In view of this they should state how particle thickness was measured. Are the values quoted a mean thickness or the maximum thickness of particles?

Authors: For flaked particles the available surface area is important for protein extraction. It is, therefore, a sensible property to measure. VIA measures the projected surface area and, assuming a constant thickness, the product of the surface area and thickness does give an approximation of the volume. Ignoring the area at the 'edges' the available surface area is approximately double the projected surface area.

Using VIA it is possible to calculate a mean thickness from the total projected surface area. This gives a mean value for the whole population of particles but, clearly, this is an oversimplification. As already pointed out, particles are usually thicker at one end. Moreover our observations indicate that the larger particles are also thicker but we have no data on how the thickness varies within a population of particles.

C.J.Scott: Impeller speed affects length of cut; aperture size affects width. Table 1, however, implies impeller speed is not important.

Authors: We appreciate that aspect ratio (i.e. the ratio of the width of a flake to its length) is an important property of a particle and one which, conceivably, will depend upon the material being flaked and the conditions employed during flaking.

According to our results meat flaked at higher speeds had a greater projected surface area (but not significantly so), implying that the particles were thinner. However, as we did not specifically measure aspect ratio we cannot confirm or deny the reviewer's comments.

P.J. Lillford: The aperture size quoted in Table 2 refers presumably to the width of the cutting orifice. Why should the width of the orifice affect particle thickness?

Authors: The thickness of the flakes produced will depend upon the extent to which it protrudes into the apertures of the cutting head. This can be best understood by considering a single, spherical piece of meat, as shown below. The arrows denote the relative motions due to the impeller and centrifugal force.