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Introduction

The fracture behaviour of cooked meat is an important aspect of its mechanical properties in relation to textural quality, as chewing meat is essentially breaking down the material in the mouth. It is also important to understand how fracture properties relate to the structure of meat to identify structural mechanisms responsible for variations in perceived texture. Of the many instrumental techniques developed to measure some aspect of the fracture process that is a good predictor of textural quality, or toughness, of cooked meat (see Szczesniak & Torgeson, 1965, and Voisey, 1976, for reviews), the most widely used are the shear presses (Warner, 1928, Bratzler, 1949; Kramer et al., 1951) and the bite tests (Volodkevich, 1938; MacFarlane & Marer, 1966). Their empirical nature makes them unsuitable for measuring fundamental fracture properties and relating these to meat structure.

Ultimate tensile strength (U.T.S.) has previously been measured on tensile strips of meat by many workers (e.g. Bouton et al., 1975; Penfield et al., 1976; Davey & Gilbert, 1977). However, there appears to have been little interpretation of the anisotropy of UTS in relation to the qualitative fracture behaviour of meat, to explain why it breaks in the way it does. Little attention has been given to the control of specimen size and strain rates used. (Voisey, 1976), factors which may affect the UTS of a viscoelastic material (Ferry, 1980).

Modern fracture mechanics, based on the work of Griffith (1921), defines toughness as the resistance of a material to the propagation of a crack through it. Toughness is then measured by the minimum energy required to propagate the fracture, or by the concentration of stress at the tip of the crack. The former can be evaluated by measurement of work of fracture, and information on the latter inferred from notch sensitivity tests. Such an approach to the measurement of toughness is a logical development in the study of meat fracture.

This paper describes work aimed at understanding the structural features of meat that determine the way in which it breaks, and how these relate to fundamental fracture measurements. Qualitative aspects of fracture behaviour are observed on simple tensile strips, and ultimate tensile strengths measured. Work of fracture and notch sensitivity of cooked meat are measured and concepts of fracture mechanics used to draw together observations in a way that suggests some mechanisms responsible for the toughness of meat.

Materials and Methods

M. Semitendinosus muscles from Friesian cross heifers were cut whilst frozen into thin slices (approx 5 mm thick) either transverse to the muscle fibre direction or parallel to the fibres running longitudinally along the muscle. These slices were individually cooked in vacuum packs in a water bath at 80°C for one hour. From the longitudinal slices, strips were cut in two directions, with the long axes of the strips parallel to the muscle fibre direction ("parallel" strips) and with the long axes of the strips perpendicular to the fibre direction ("perpendicular" strips).

Tensile tests. Detailed qualitative observations on the fracture of this cooked meat were made by tensile tests on notched strips in a variety of

orientations, taking video recordings and still photographs of salient events during the fracture process. UTS measurements were made by taking parallel and perpendicular tensile strips from longitudinal cooked muscle slices, template cut to a gauge width of 6-4 mm and gauge length 34.2 mm. These were stretched to fracture on an Instron testing machine at extension rates of 50, 125 or 250 mm min⁻¹ (corresponding to strain rates 1.46, 3.65 or 7.30 min⁻¹ respectively). UTS was taken as maximum observed load divided by nominal cross-sectional area.

Work of fracture. Work of fracture was measured under quasi-static fracture propagation conditions (i.e. slow crack growth). Work of fracture for rupture running parallel to the muscle fibres ("along fibres") was measured on tear test specimens according to the method of Purslow (1983) on an Instron, using an extension rate of 50 mm min⁻¹. Work of fracture was measured as the energy used to slowly propagate a tear along the specimen divided by the area through which the propagation occurred. The work of fracture for cracks spreading across transverse slices of cooked M. semitendinosus ("between fibres") was measured using a "pure shear" configuration (Rivlin & Thomas, 1953) with typical gauge width of 40 mm and length of 15 mm. Work of fracture was again measured as energy used in rupture divided by nominal area through which propagation occurred. An extension rate of 50 mm min⁻¹ was used.

Notch sensitivity. The relationship between nominal breaking stress and the length of pre-cut notches across this width of the specimen (notch-sensitivity) was measured on parallel tensile strips from cooked longitudinal M. semitendinosus slices cut to a gauge width of 30 mm and gauge length of 120 mm. Notches were cut perpendicular to the fibres in one edge of the specimens, ranging in width up to 15 mm (half total width). Several strips were also left unnotched. All strips were extended at 125 mm min⁻¹ in an Instron and nominal breaking stress (i.e. maximum load/full cross-sectional area) recorded.

Results and Discussion.

Figure 1 shows the propagation of fracture across a transverse slice. A notch cut in the left hand side of the specimen has opened up considerably and is growing left to right. Small scale ruptures or cavitations have occurred at muscle fibre boundaries, i.e. at the perimysium. The macroscopic failure subsequently joins up a series of these small cavities, so that the path of fracture mainly lies around fibre bundles rather than crossing through them. Bridging the crack tip are light strands of highly extensible connective tissue, which are the last structures to break. This observation supports the view that the original small scale ruptures occurred at interfaces within, or at the surface of, the perimysium leaving debonded planes of connective tissue intact to form these bridging strands. This is consistent with the hypothesis proposed by Carroll et al (1978) from their similar qualitative observations that separation occurs at the endomysial-perimysial interface. This strong involvement of connective tissue at the perimysial level in fracture was also observed in other orientations. Longitudinal strips pulled perpendicular to the fibre direction showed separation of intact muscle fibre bundles with a network of fine connective tissue strands bridging the gap. Figure 2 shows a notched strip that has been pulled parallel to the fibre direction. The initial rupture was merely to split back the perimysial interface between fibre bundles perpendicular to the expected crack path. Qualitatively, therefore, perimysial connective tissue seems to be an important sub-structure which to some extent determines the fracture behaviour of cooked meat in all test orientations.

Ultimate Tensile Strength. The UTS measurements taken highlight the structural anisotropy of the cooked meat in the longitudinal slice; when testing perpendicular to the fibres no fibre bundles are broken and the material merely separates at the perimysium. On the other hand, when testing parallel to the fibres, all the fibres in a cross section must be broken. Figure 3 shows the mean strength of perpendicular strips at the three different strain rates used. The apparent trend for tensile strength to increase with strain rate is not statistically significant (P>0.1). Mean values of UTS lie in the range 20-30 kNm⁻². Figure 4 shows the mean UTS of parallel strips tested at the same three strain rates. There is no effect of strain rate on UTS above the specimen to specimen variability, which was considerable. Mean values of UTS here lie in the region of 300-400 kNm⁻². This is an order of magnitude greater than mean perpendicular UTS values in the range of strain rates studied. Considerable anisotropy in strength shows that the cooked and partially gelatinised perimysium, or the interface between the perimysium and fibre bundles, is much less strong than the cooked fibre bundles it surrounds. This shows why the perimysium should be the principal fracture site.

A Fracture Mechanics approach: (a) Worth of fracture.

Griffith (1921) outlined two conditions necessary for a crack to grow in a stressed body, and hence two criteria by which fracture toughness can be measured; (a) the balance of energy consumed and released as a crack propagates, and (b) the concentration of stress at the tip of the crack required to break local bonds. The former can be practically determined as the work of fracture. Table 1 shows mean values of work of fracture for tears running parallel to the fibres along their length ("along fibres") and for fractures passing between fibres across a transverse slice ("between fibres"). Both are due to the fracture resistance of the perimysium and are relatively low in absolute terms, explaining why the perimysium is the preferred fracture site. The difference between the two values may be ascribed to three factors. Firstly, cavitation at fibre bundle boundaries only occurs in the transverse test orientation and is a process which irreversibly absorbs energy. Secondly, the more tortuous crack path around muscle fibre bundles across the transverse slice means that the amount of surface area created across a nominal cross-section is higher in this testing direction, and thirdly, differences in loading configurations between the two tests may result in differing amounts of generalised plasticity occurring in the bulk of each specimen. The work of fracture for cracks propagating across and through the muscle fibres would appear to be much greater than the values reported for perimysial fracture in Table 1 because all attempts so far to propagate cracks in this direction have resulted in the crack deviating to run along the weaker fibre bundle boundaries, at right angles to the desired path.

(b) Notch sensitivity. Griffith's (1921) second criterion for fracture propagation was that there should be sufficient stress intensity around the tip of a crack to break atomic bonds by the local concentration of sufficient strain energy. The concentration effect can be viewed as a mechanism for strain energy transfer from the bulk of the specimen to the fracture site at the tip of the crack. Transfer efficiency depends on the length and sharpness of the crack; a sharp crack tip results in a high stress concentration. If the tip is massively blunted there is poor stress concentration and transfer of strain energy, so the fracture is more difficult. Such crack blunting occurs when trying to propagate cracks across the fibres, as in figure 2. The opening of the perimysial interface effectively blunts the tip of the crack. Gordon (1980) has extended this idea to the case of an array of uniaxial filaments (here representing muscle fibre bundles) bonded together with an intervening

material (here representing the perimysium) providing an interface. If the fibrous elements are very well bonded together through strong interfaces the strain energy released by the fracture of one fibrous element is able to be transferred by the sharp crack to affect the fracture of successive elements and the breaking stress of a notched specimen will fall off very rapidly with crack length. This is known as notch-sensitive behaviour (Kelly, 1966). For brittle notch-sensitive continuum in plane stress the nominal breaking stress σ_b is proportional to $(1/a)^{1/2}$, where a is the crack length. Hedgepeth (1961) calculated a notch sensitivity relationship for a uniaxial array of discrete filaments which is of similar general form to the continuum case. On the other hand, if the intervening material between the fibrous elements provides little or no interfacial integrity, then the debonding effect means there is no opportunity to transfer energy from a broken element to affect the failure of others, and the elements fail independently. In this case the nominal breaking stress decreases linearly in single proportion to the remaining number of intact elements;

$$\sigma_b = \sigma_n (1 - a/W) \quad (\text{Kelly, 1966})$$

where σ_n is the nominal (unnotched) breaking strength and W the total width. This behaviour is called notch-insensitive.

Figure 5 shows the relationship between nominal breaking stress and crack length in cooked meat strips, with the crack direction perpendicular to the fibre direction (direction of applied load). It is apparent that this material is completely notch-insensitive. There is little or no shear communication of strain energy from fibre bundle to bundle, showing why it is difficult to propagate fracture across the fibre direction.

Conclusions.

The perimysial connective tissue appears to be an important level of structural organisation in cooked beef muscle in relation to its fracture behaviour. The low transverse strength and work of fracture of this connective tissue layer explains the qualitative observation of the meat being easily separable into individual fibre bundles. The notch insensitivity result explains why propagation of fracture across the fibre direction is much more difficult. These results suggest a two-phase composite model for cooked meat in relation to fracture with stiff, strong uniaxial fibrous elements (muscle fibre bundles) linked by a weaker and more compliant matrix (gelatinised perimysial connective tissue) and with an interface between the two phases which is weak in shear. Such a conceptual model may prove useful in future work on the fracture properties of cooked meat.

Table (1). Works of fracture along and between fibres.

	"Along fibres"	"Between fibres"
Mean work of fracture (kJm ⁻²)	0.42	1.83
Standard error	0.035	0.13
No. specimens	19	17

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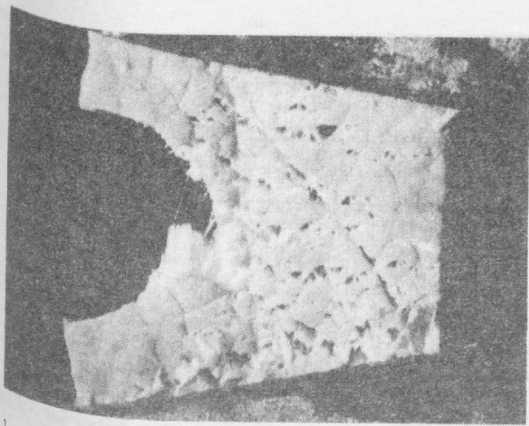


Fig. 1. Propagation of rupture across a transverse specimen under tension.

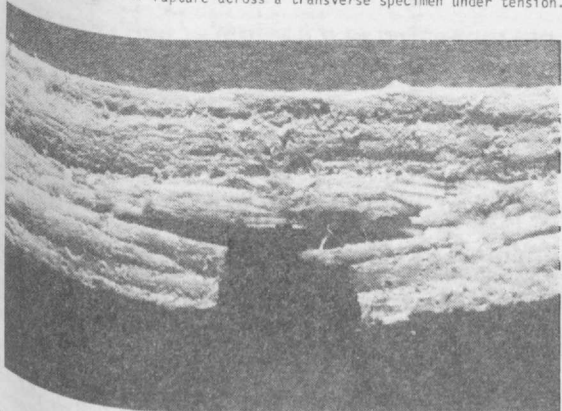


Figure 2. Notched strip pulled parallel to the muscle fibre direction, showing initial splitting back of perimysial interface.

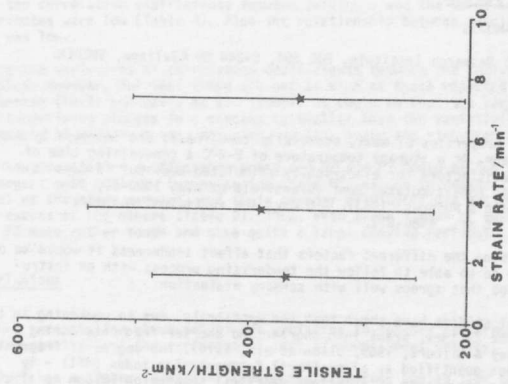


Fig. 4. Tensile strength v. strain rate parallel to muscle fibre direction.

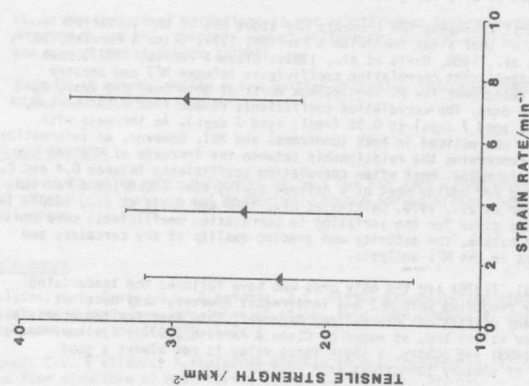


Fig. 3. Tensile strength v. strain rate perpendicular to fibre direction.

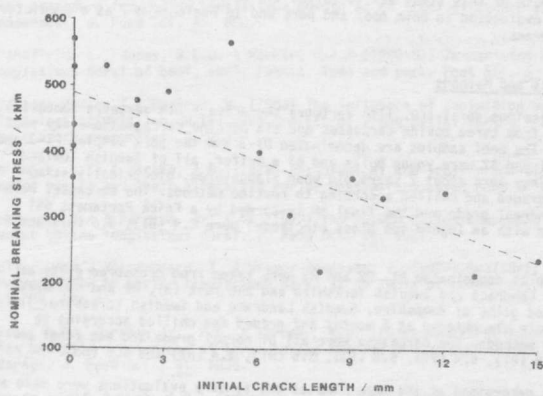


Figure 5. Notch sensitivity of cooked m. semitendinosus.