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ON THE VISCOELASTIC BEHAVIOUR OF BEEF MEAT UNDER COMPRESSION LOADING

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Abstract

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A method for the characterising of the behaviour of the beef meat at compressive loading was investigated. Both compressive and relaxation tests have been used. Results of the relaxation tests have shown that the boiled beef can be described in terms of the Maxwell model of the strain behaviour. Parameters of this model are dependent on the values of the loading force. The description of the observed behaviour of the beef under compressive loading thus needs some other model. It is shown that the obtained results on the compressive loading of the beef can be explained in the framework of the hyperelastic – viscous body.

beef, compressive loading, relaxation test, rheology, Maxwell model, hyperelasticity

The texture of food is related to how the food deformation and breaks when it is eaten. In practise, many methods are used to evaluate meat texture. They can be divided into two groups: instrumental methods (known as objective) and sensory methods (which are fundamentally subjective). In the framework of instrumental methods different types of forces as compression, tension or shear could be applied (Tornberg, 1996). From the results obtained up to now one can conclude that many foods such as cheese, dough, beef and many others exhibit large strain, viscoelastic behaviour. Such behaviour is generally observed for number of materials like biological materials such as human organs (Miller, 1999; Miller and Chinzey, 2002), food (Goh et al., 2003), rubbers (Quigley et al., 1995; Diani et al., 2004), polymers (Williams, 1980; Wang and Yang, 1992) and some foams (Zhang et al., 1997; Yang and Shim, 2004).

In order to characterise these materials, both the strain and the time-dependent behaviour must be measured and modelled accurately. For foods consistent material data are not obtainable because of the significant material variation between different blocks and batches. This phenomenon is well documented e.g. for cheeses (Prentice, 1992). Thus the material data is not accumulative and has to be collected for each bath. Successful methods for characterising foods should be simple, quick and economic in terms of time and material.

In this study a method for the characterising the behaviour of the beef meat at compressive loading was investigated. This loading corresponds to some procedures for the evaluation of sensory characteristics. The aim of this effort consists in the obtaining of a reliable constitutive equation which should be applicable for the numerical simulation of general loading processes.

EXPERIMENTS

For the experiments a beef described in details by Sochor et al. (2005) has been used. The *M. longissimus dorsi* was removed from each carcass for mechanical testing. Meat was vacuum packaged prior to cooking in a water bath until the internal temperature reached 70 °C. The cores were removed parallel to the muscle fibre orientation (about 6 cm long x 1 cm high x 1 cm wide). Then the cubes were prepared (side 1 cm) for the compression test.

The specimens were compressed using TIRA testing machine. During uniaxial compression specimens were compressed to 80% deformation at a crosshead speed of 20 mm/min. The integrated software converted the force crosshead displacement to stress – strain data. Stress measures were calculated on the assumption that there is a very little or no change in volume of beef during compression.

In the next step stress – relaxation tests were performed. These tests represent a common method for determining the viscoelastic behaviour when a step strain loading is applied and the stress is allowed to decay with time.

All experiments were performed at the room temperarture.

EXPERIMENTAL RESULTS

Compressive tests

The following procedure converted force F(t) displacement Δh(t) record to stress –strain data:

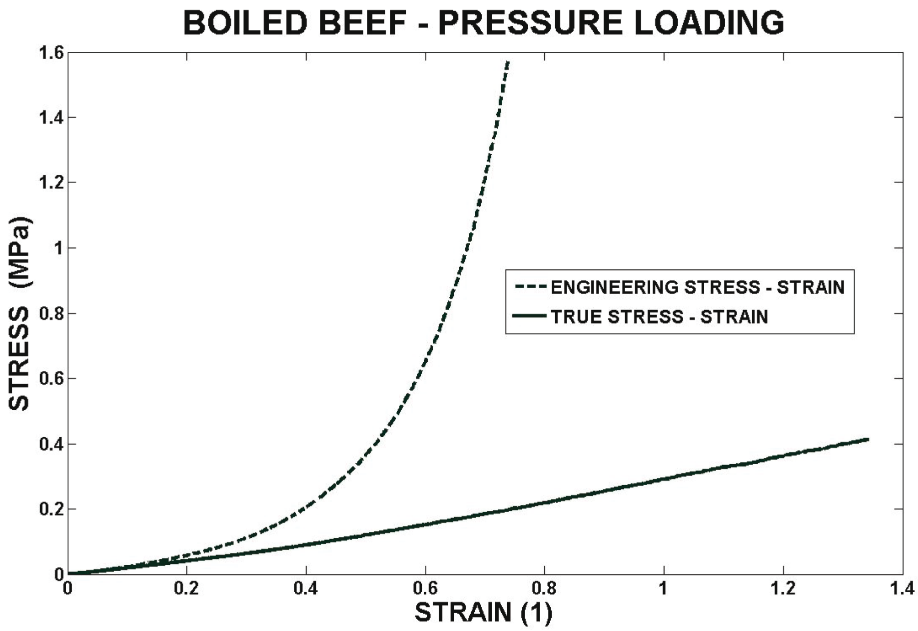
$$\varepsilon = \frac{\Delta h}{h_o}$$

$$\sigma = \frac{F}{A_o},$$

where ε is the engineering strain, h_o is the original height, Δh is the change in the height, σ (t) is the engineering stress at time (t), o is the initial cross – section of the specimen. These data can be used for the evaluation of the true strain and true stress (Calzada and Peleg, 1978):

$$\varepsilon_{true} = \ln(1 + \varepsilon)$$
$$\sigma_{true} = \sigma e^{-\varepsilon}.$$

The stress is calculated usually of the assumption that there is a little or no change in volume of beef during its compression. Example of the stress – strain dependence is given in Fig. 1.



1: *The dependence of stress on the strain*

It is evident that the difference between engineering and true characteristics are meaningful from a certain value of strain. The obtained results can be fitted by functions:

Engineering stress – strain:

$$\sigma = 7.4545\varepsilon^3 - 3.9816\varepsilon^2 + 0.8381\varepsilon \quad R^2 = 0.9952$$

True stress – strain:

$$\sigma_{true} = -0.0562\varepsilon_{true}^3 + 0.1835\varepsilon_{true}^2 + 0.1625\varepsilon_{true} \quad R^2 = 0.9953$$

The values of the coefficients represents the average from 10 measurements. The dependences stress – strain don't give any evidence of the material viscosity. This evidence can be obtained from relaxation tests.

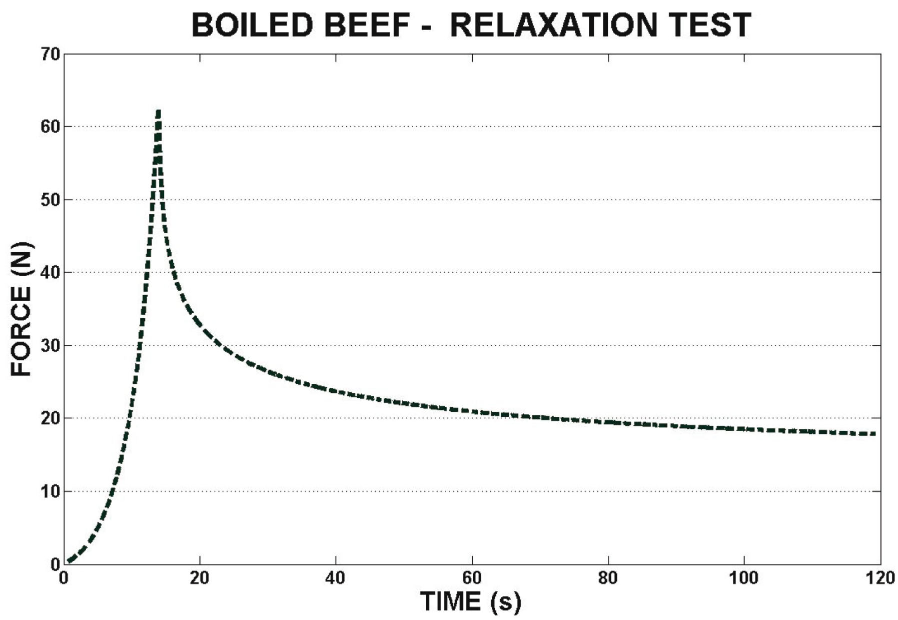
Relaxation tests

During the relaxation test the samples are compressed until a prescribed value of the force is achieved. The compression anvil is than held in positron for some time (usually few minutes) to mantain a constant strain. This test is widely used for the evaluation of meat quality (Mallikarjunan and Mittal, 1995; Lepetit et al., 1986; Lachowicz, 2003). During our tests the specimens of beef were compressed to different values of strain. Corresponding forces Fmax,strains and stresses are repoted in Table I together with the value of corresponding strains.

I: *Values of initial stresses and strains*

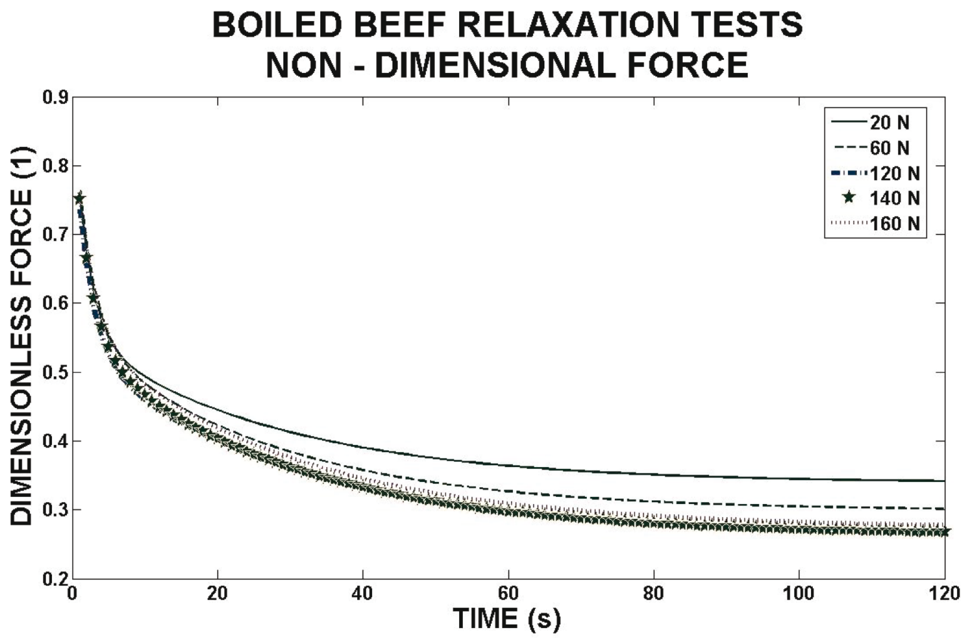
FORCE F_{max} (N)	20.69	60.7	127.29	141.42	164.22
Engineering stress (MPa)	0.21	0.61	1.28	1.41	1.64
TRUE STRESS (MPa)	0.12	0.26	0.37	0.37	0.39
Engineering strain	0.4255	0.5824	0.7122	0.7329	0.7639
True strain	0.4997	0.9171	1.2200	1.2400	1.2800

In Fig. 2 an example of the experimental record is given.



2: *Example of an experimental record: force – time during the relaxation test*

The decrease of the force with time is the evidence of the viscoelastic behaviour of the beef during its compression loading. For the evaluation of the viscoelastic behaviour the initial part of the record shown in Fig. 1 is omitted. The decrease of the force with the time is shown in Fig. 3.



3: *The time dependence of the dimensionless force*

The forces are normalized to the value of the maximum of the force F_{max}. The experimental dependence may be fitted by the function:

$$F = F_o + F_1 \exp\left(-\frac{t}{\tau_1}\right) + F_2 \exp\left(-\frac{t}{\tau_2}\right),$$

where F is the force at time t, Fo is some residual force which is achieved at $t \to \infty$, F_1, F_2, τ_1 and τ_2 are the material parameters. This function corresponds to the Maxwellian models of viscoelastic behaviour that include a spectrum of relaxation times (Nussinovith et al., 1989). This model can be expressed in terms of the stress:

$$\sigma(t) = \sigma_o + \sigma_1 \exp\left(-\frac{t}{\tau_1}\right) + \sigma_2 \exp\left(-\frac{t}{\tau_2}\right).$$

The parameters of this equation are given in Table II.

II: *Parameters of the relaxation function*

FORCE Fmax (N)	σ_1 (MPa)	τ_1(s)	σ_2 (MPa)	τ_2 (s)	σ_o(MPa)	R^2
20.69	0.07031	2.0756	0.044505	27.7778	0.07008	0.9995
0.6070	0.2032	2.3170	0.1591	26.8312	0.1812	0.9967
1.2729	0.4254	2.1317	0.349	28.8351	0.3337	0.9958
1.4142	0.4742	2.3116	0.3964	28.5796	0.3732	0.9964
1.6422	0.5238	2.2507	0.4785	28.5470	0.4495	0.9968

The corresponding elastic modulus (G_i) of each element and the viscosity coefficient (η_i) are determined according to the equations:

$$G_i = \frac{\sigma_i}{\varepsilon_o}$$

$$\eta_i = G_i \tau_i,$$

where ε_o is the initial strain given in Table II. The values of the moduli and viscosities are given in Table III.

III: *Rheological properties of the boiled beef*

FORCE Fmax (N)	G_1 (MPa)	η_1(MPas)	G_2 (MPa)	η_2 (MPas)	G_o MPa)
20.69	0.1652	0.3430	0.1046	2.9054	0.1647
0.6070	0.3489	0.8084	0.2732	7.3297	0.3111
1.2729	0.5972	1.2733	0.4900	14.1301	0.4685
1.4142	0.6470	1.4956	0.5409	15.4577	0.5092
1.6422	0.6857	1.5433	0.6264	17.8816	0.5884

It is evident that the parameters of the rheological model are strongly dependent on the values of the force or stress, respectively. It means that the strain behaviour of the tested beef exhibits significant non – linear viscoelastic features. This behaviour cannot be described only in terms of the Maxwell model mentioned above. In order to describe the observed stress – strain behaviour of the beef meat we have used an analogy in the similarity between stress – strain curves obtained in this work with those obtained for some polymeric foam (Zhang et al., 1997), rubber (Yang et al., 2000) and some other polymeric materials (Wang and Yang, 1992). The description of these results is given in terms of the visco – hyperelastic constitutive equation. According to this theory which is well described e.g. by Yang and Shim (2004) the uniaxial stress consists of two parts. The first part describes the hyperelastic strain behaviour for very small strain rate which can be taken as a zero. This part is than expressed as:

$$\sigma^e = \frac{\lambda^2 - 1}{\lambda^2} \left\{ a + b(3\lambda^2 + 5) + \frac{c}{2\lambda^2} \right\},$$

where λ is the stretch which describes the strain of the material. The relationship between stretch λ and engineering strain ε in the direction of the uniaxially applied load is: $\lambda = 1 + \varepsilon$ (ε is taken as the negative value for the compression loading).

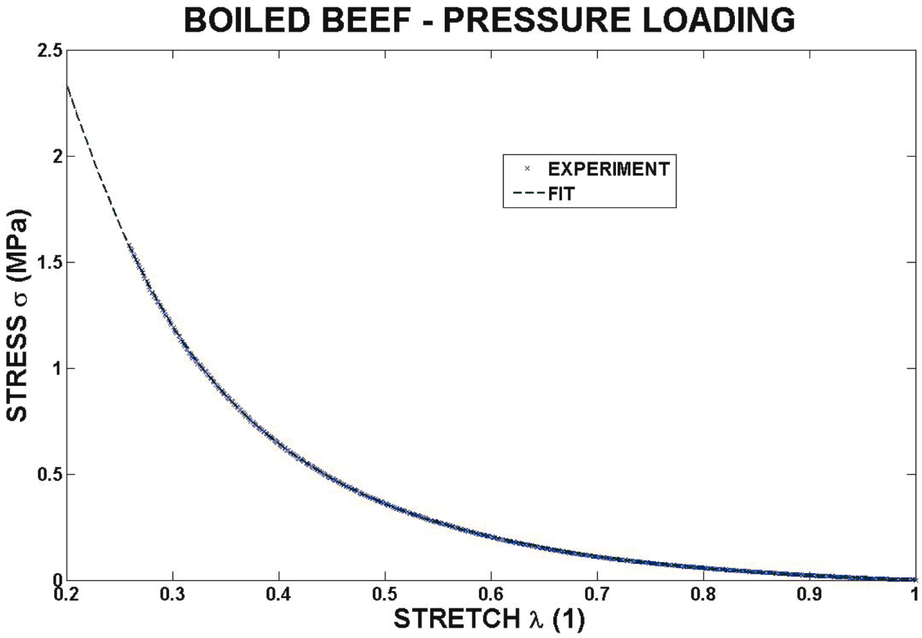
This relation is followed by formulation of a viscoelastic constitutive model for finite deformation. This procedure leads to the expression for the uniaxial stress

$$\sigma = \sigma^e + 4\lambda^2 \int_0^t (\lambda^2 - 1)^2 \left(b_1 \lambda + \frac{b_2}{\lambda} + \frac{b_3}{\lambda^2} \right) x\exp \left(-\frac{t - \tau}{b_4} \right) \dot{\lambda} d\tau.$$

The stretch rate is equal to the engineering strain rate, i.e.

$$\dot{\lambda} \equiv \frac{d\lambda}{dt} = \frac{d\varepsilon}{dt} \equiv \dot{\varepsilon}$$

The stress – stretch dependence is shown in Fig. 4.



4: *The dependence of the stress on the stretch*

The crosshead speed of the testing machine V = 20 mm/min corresponds to the strain rate:

$$\dot{\varepsilon} = \frac{V}{L},$$

where L is the initial height of the specimen (10 mm). The value of the strain rate is about 0.033 s^{-1}. If neglect this strain rate we can evaluate of the parameters which occur in the expression for the stress σ^e. Non – linear fitting leads to the values of these constants:

a = –0.2572 MPa, b = – 0.02262 MPa, c = 0.003497 Mpa.

The correlation R2 is very high. Its value cannot be distinguished from one.

It is evident that the verification of the hypothesis that the boiled beef behaves as a hyperelastic – viscous solid should be supported by other experiments performed for different strain rates.

CONCLUSIONS

The experiments performed in the given paper verified that the strain behaviour of the boiled beef is generally viscoelastic. Results of the relaxation tests show that the parameters of the Maxwell model of the strain behaviour are dependent on the values of the loading force. The description of the observed behaviour of the beef under compressive loading thus needs some other model. It is shown that the obtained results on the compressive loading of the beef can be explained in the framework of the hyperelastic – viscous body. The verification of this hypothesis will be subject of the forthcoming papers.

SOUHRN

O viskoelastických vlastnostech hovězího masa při tlakovém zatěžování

Práce obsahuje výsledky zatěžování vzorků vařeného hovězího masa v tlaku. Experimenty byly provedeny při rychlosti upínací hlavy 20 mm/min. Výsledky byly interpretovány závislostí napětí – deformace a napětí – skutečná deformace. Pro získání podkladů pro popis reologického chování tohoto materiálu byly provedeny zkoušky na relaxaci napětí. Výsledky testů ukazují, že pro jednotlivé hodnoty aplikovaného napětí je možné použít modelu Maxwelova tělesa. Nicméně závislost těchto parametrů na aplikovaném napětí vyžaduje použití poněkud komplexnějšího modelu deformačního chování. Na základě porovnání výsledků dané práce s výsledky získanými pro jiné materiály byl použit model hyperelastického, viskózního materiálu. Tento model spojuje napětí a poměrné zkrácení vzorku. Byly stanoveny parametry příslušné konstitutivní rovnice. Pro další popis pak bude nezbytné realizovat experimenty s různými hodnotami rychlosti deformace.

hovězí maso, tlakové zatěžování, relaxační test, reologie, Maxwellův model, hyperelasticita

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