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Citation: AIP Conference Proceedings **1769**, 180004 (2016); doi: 10.1063/1.4963607
View online: http://dx.doi.org/10.1063/1.4963607
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1769?ver=pdfcov
Published by the AIP Publishing

Experimental and Numerical Investigation of Ram Extrusion of Bread Dough

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Abstract: An experimental and numerical study on ram extrusion of bread dough was conducted. A laboratory ram extrusion rig was designed and manufactured, where dies with different angles and exit radii were employed. Rate dependent behaviour was observed from tests conducted at different extrusion speeds, and higher extrusion pressure was reported for dies with decreasing exit radius. A finite element simulation of extrusion was performed using the adaptive meshing technique in Abaqus. Simulations using a frictionless contact between the billet and die wall showed that the model underestimates the response at high entry angles. On the other hand, when the coefficient of friction value was set to 0.09 as measured from friction experiments, the dough response was overestimated, i.e. the model extrusion pressure was much higher than the experimentally measured values. When a critical shear stress limit, $\tau_{\max}$, was used, the accuracy of the model predictions improved. The results showed that higher die angles require higher $\tau_{\max}$ values for the model and the experiments to agree.

Keywords: *Bread dough; adaptive meshing; extrusion pressure; critical shear stress limit*

INTRODUCTION

Extrusion is one of the common manufacturing processes in bread dough production lines. The shape of the dough after extrusion, also known as the extrudate, depends on the geometry of the extruder as well as the mechanical behaviour of dough. The extruder's die geometry can be varied in terms of the mouth opening and the die mouth angle. In addition, bread dough has been shown to behave as a viscoelastic material, as reported by various authors [1,2,3]. The complex mechanical behaviour of dough combined with the abrupt geometry change in the die mouth, makes modelling of dough ram extrusion a challenging task.

To investigate the behaviour of dough during extrusion, a laboratory ram extrusion rig was designed and manufactured (see Figure 4(a) for schematic of the experimental setup). Experimental extrusion pressures were then compared to numerical model predictions performed using the commercially available finite element software Abaqus [4]. Details of the experimental work are given in the next section. This is then followed with the numerical model that aims to predict the behaviour of dough during extrusion. Issues such as the severe mesh distortion encountered in the model and the complex contact behaviour between the dough surface and the extrusion die wall are discussed.

EXPERIMENTAL

A simple mixture of wheat flour, salt and water was used to prepare bread dough. The flour used was purchased from Wessex Mill, Oxford, UK. The starch and gluten contents in the flour are 86.1% and 13.9%, respectively, which were determined from dough washing procedures [3]. A mixture of 198.5g of wheat flour, 120g of distilled water and 1.5g of salt was mixed for three minutes using an instrumented laboratory 6-pin mixer at a constant speed in ambient conditions.

The extrusion rig used consisted of a 25 mm diameter Poly (Methyl Methacrylate) (PMMA) barrel in which the internal bore was polished. The barrel was split in two halves to facilitate filling and to avoid air bubbles. Each half was filled with dough and the two halves were then clamped together. A steel piston (ram) with a PTFE plug was used with an Instron 5543 testing machine. The loads were measured using 5 kN and 100 N load cells. The dies were mounted on the base of the barrel and then placed on a frame to allow the extrudate to flow out freely. Dies with different arbitrary angles were used for the experiments, as shown in Figure 1. Dies 26º a, 26°b and 26ºc have a 26° entry angle but varying exit diameter whereas dies 26°a, 44º, 72° and 108º all have the same exit diameter but they vary in terms of entry angle. The ram extrusion speeds were 50 mm/min (for all dies shown in Figure 1), 200 mm/min (for the three 26º dies) and 500 mm/min (for the 44º, 72° and 108º dies).

ESAFORM 2016
AIP Conf. Proc. 1769, 180004-1–180004-6; doi: 10.1063/1.4963607
Published by AIP Publishing. 978-0-7354-1427-3/$30.00

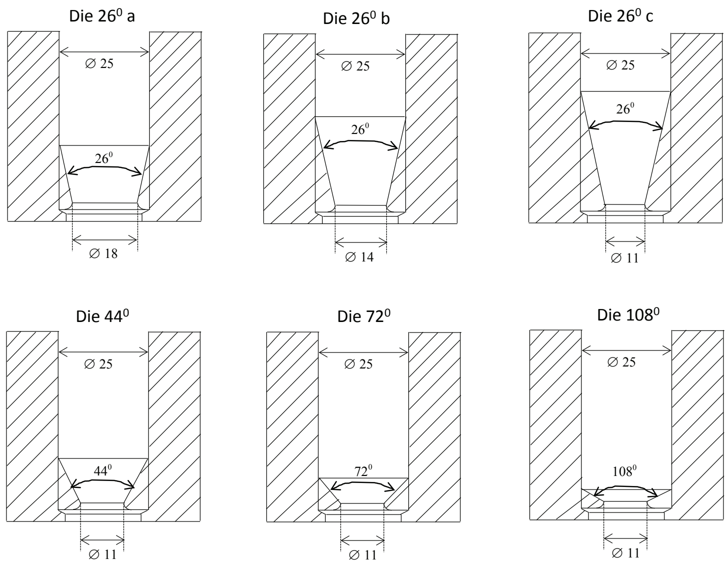

Figure 1. Dies used for wheat flour dough extrusion. All dimensions shown are in mm.

The experiments were performed at 22 ^{0}C and 50 % relative humidity. Since the extrusion rig was set up vertically, steady state extrusion pressures were achieved by extruding the dough into Glycerol (density of 1.25 g/ml) to counteract the effect of gravity on the experimental results, as demonstrated by [5].

Examples of the extrusion experimental results are shown in Figure 2 for 26^{0}a and 72^0, at both high and low speeds. Rate dependent behaviour is observed with higher pressure recorded as speed increased. Notice that the initial rise in extrusion pressure is due to the dough being compressed by the ram until it is consolidated into the barrel and die, with a steady state reached thereafter. The steady state results from all tests are shown in Table 1. Decreasing the output radius of the dies (dies 26° a-c) resulted in higher extrusion pressures. In addition, increasing the entry angle from 26° to 72º (dies 26ºc to 72° - exit diameter constant at 11 mm) resulted in a very significant increase in pressure. However, increasing the die entry angle even further (108º) did not lead to further significant increases in pressure at the speed of 50 mm/min.

Table 1: Stead state extrusion pressure data from various dies

Die	26°a	26°b	26°c	44°	72°	108°
Steady state pressure (kPa) 50 mm/min	0.90 ± 0.19	3.64 ± 0.18	9.72 ± 0.78	16.64 ± 1.11	35.07 ± 1.02	39.20 ± 2.43
Steady state pressure (kPa) [1]200 mm/min [2]500 mm/min	2.13 ± 0.44[1]	5.93 ± 0.26[1]	18.82 ± 1.07[1]	32.23 ± 3.01[2]	69.91 ± 4.91[2]	84.49 ± 2.54[2]

Rheological tests under different loading conditions, namely uniaxial compression, uniaxial tension, cyclic-compression and relaxation-compression were taken from an earlier study [3]. The uniaxial tension test was performed by clamping both ends of a sample and by pulling it in opposite directions at a fixed strain rate using a universal testing machine [6]. For uniaxial compression tests, the load direction is opposite to the load direction of the uniaxial tension test. Cyclic compression tests were conducted by loading and unloading a sample under compression mode at the same strain rate. The re-loading of the sample was activated once the stress in the unloading part becomes zero. Finally, stress relaxation was conducted under compression mode, where a specimen was compressed to a required strain which was then held fixed for a period of time while the force decay was recorded. All compression experiments were conducted under lubricated conditions. The experimental results from these tests are shown in Figure 3.

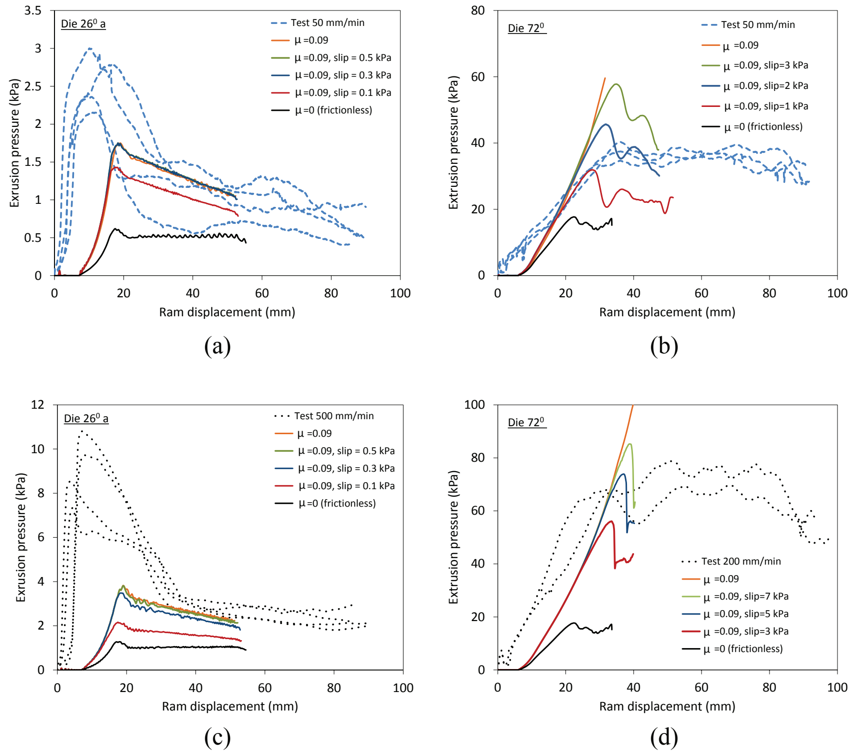

Figure 2. Comparison between experimental data and extrusion model for two dies (Die 26ºa, Die 72°) at low (50 mm/min) and high (500 mm/min and 200 mm/min respectively) extrusion speeds. Experimental results are shown with dotted lines.

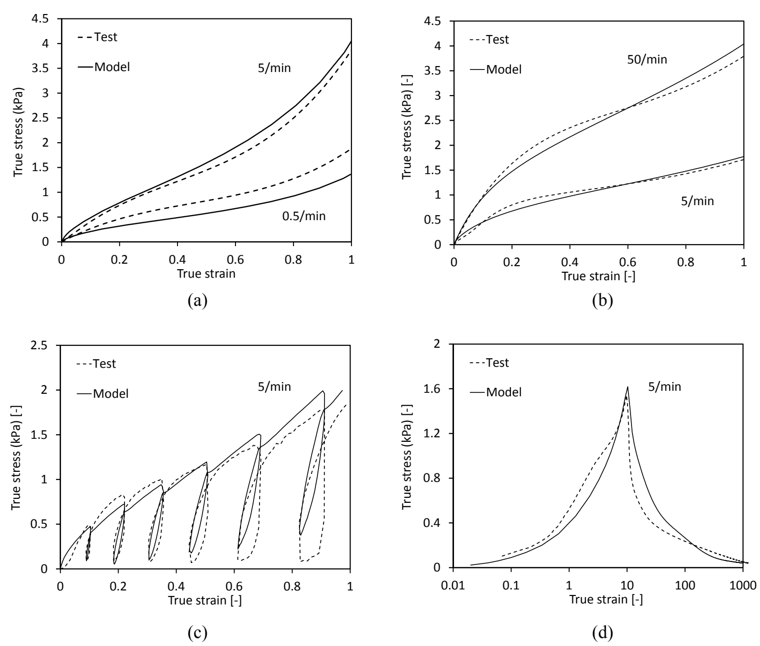

Figure 3. Calibration of material model with bread dough experimental results: (a) uniaxial tension; (b) uniaxial compression; (c) cyclic-compression; and (d) relaxation-compression.

Finally, attempts to measure the coefficient of the friction between the dough and the barrel surface during extrusion was obtained by placing a known mass of dough on to one half of the lubricated (paraffin oil) extrusion barrel [5]. The extrusion barrel was then attached onto a combination reversing protractor. The kinetic coefficient of friction was determined by allowing the dough sample to slide and subsequently altering the angle until no sliding occurred. The value of μ was calculated from $\mu = \tan\theta$, where θ is the angle at which the dough sample stopped sliding. Several dough samples of mass varying from 3 to 30 grams were used for the experiment, giving an average resting angle of ~5º and a coefficient of friction of $\mu = 0.09$.

MODELLING

For simplicity, even though dough is a two phase starch/gluten particulate composite [3], a continuum material model is assumed when simulating the ram extrusion process. For this, the visco-hyperelastic model combined with the Mullins effect was used, where the former model is based on the work by [6], and the latter model is added here to simulate stress softening occurring as evidenced in cyclic loading data. The viscoelastic part of the model assumes a separable time and strain dependent material behaviour [7]. The relaxation stress under a step strain loading history is defined as a function of time, $g(t)$, and strain, $\sigma_0(\varepsilon)$ through $\sigma(\varepsilon,t) = \sigma_0(\varepsilon)g(t)$, where the former is represented by the Prony series [3] with five g_i parameters corresponding to the five relaxation times ξ_i of 0.1, 1, 10, 100 and 1000 s. The stress, σ_0, is obtained using the van der Waals hyperelastic potential, where the stress is given as $\sigma_0(\lambda) = \frac{\partial U}{\partial \lambda}\lambda$, with U being the hyperelastic potential. The stress under uniaxial tension and compression can be derived as:

$$\sigma_0(\lambda) = \psi\lambda\left(\lambda - \frac{1}{\lambda^2}\right)\left[\frac{\sqrt{\lambda_m^2 - 3}}{\sqrt{\lambda_m^2 - 3} - \sqrt{\lambda^2 + 2\lambda^{-1} - 3}} - a\sqrt{\frac{\lambda^2 + 2\lambda^{-1} - 3}{2}}\right] \quad (1)$$

where λ is the stretch ratio, ψ is the instantaneous initial shear modulus, λ_m is the locking stretch constant, and a is the global interaction parameter. The Mullins model is intended to simulate stress softening under cylic loading using a damage variable, η, which varies with the deformation [4,8]:

$$\eta = 1 - \frac{1}{r}\operatorname{erf}\left(\frac{U_{dev}^m - \tilde{U}_{dev}^m}{m + \beta U_{dev}^m}\right) \quad (2)$$

where $\tilde{U}_{dev}^m$ is the deviatoric part of the strain energy density or potential U of the hyperelastic model, and U_{dev}^m is the maximum value of $\tilde{U}_{dev}^m$ at a material point during its deformation history. The other parameters, r, m and β are material parameters, and $\operatorname{erf}(x)$ is the error function [8]. The model was fitted with the dough test data under different loading conditions (using a least squares method [7]), namely uniaxial compression, uniaxial tension, cyclic-compression and relaxation-compression, as depicted in Figure 4. The Mullins model (Eq. 2), which influenced the unloading part of the cyclic test was then included to improve the unloading-reloading part of the test through a single element model simulation in the finite element model. Note that the constant m was set to be equal to zero, which implies a significant amount of damage at low strain levels [4]. The calibrated parameters are shown in Table 2.

Table 2. Material parameters of bread dough.

Material constants	Values
ψ (kPa)	4.6
λ_m	7
a	0.4
g_i (at ξ_i = 0.1, 1, 10, 100, 1000, and ∞ s)	0.6, 0.22, 0.12, 0.05, 0.009, 0.001
r	1.1
β	0.3
m	0.0

A finite element simulation of extrusion was performed in Abaqus/Explicit using axisymmetric elements. The Abaqus/Explicit procedure was selected due to its ability of solving highly discontinuous, non-linear problems whilst not requiring as much disk space as Abaqus/Standard [4]. A schematic of the model is shown in Figure 4(a). The billet represents dough being forced through the barrel with dies at different angles and exit radii as shown in Figure 1. The material parameters in Table 2 are assigned to the billet and the boundary conditions used in the model are as shown in Figure 4(a). At the top of the billet, a constant velocity equal to the experimental crosshead speed of the ram was applied as shown. The CAX4R elements were used which were linear, 4 node, axisymmetric quadrilateral, reduced integration elements. Both frictionless conditions and a Coulomb frictional contact was defined at the dough and die wall interface in order to study the effect of friction on the extrusion. More details on the numerical implementation of the frictional models are discussed in [4].

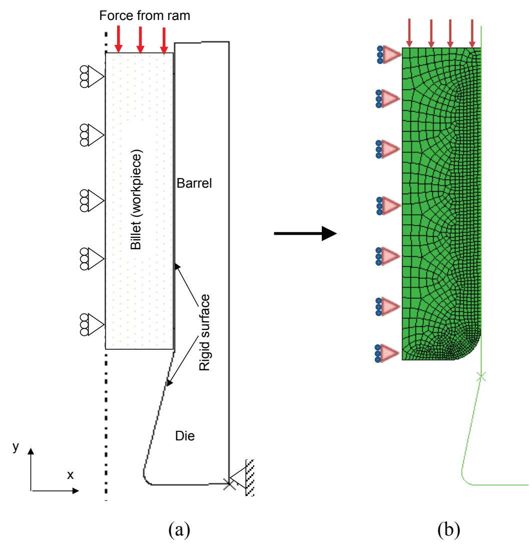

Figure 4. (a) Schematic of dough extrusion simulation; and (b) mesh and boundary conditions.

In an attempt to avoid severe mesh distortion, the mesh shown in Figure 4(b) was introduced. In addition, the adaptive meshing ALE technique was used [4]. The latter enables a high-quality mesh throughout the analysis, even when large deformations occur, by allowing the mesh to move independently to the material. The model fit to the extrusion test data at different rates using the frictionless condition is shown in Figure 2. Frictionless condition here refers to a zero coefficient of friction, μ, between the billet and the die. It is observed that the model underestimates the extrusion test data for all dies and extrusion speeds. The effect of a non-zero coefficient of friction assigned between the die wall and the billet surface on the model results was investigated.

Examples of the comparison between the model and the extrusion test data at different rates corresponding to the experimentally determined coefficient of friction of $\mu = 0.09$ are shown in Figure 2 (curve $\mu = 0.09$). It is observed that except for Die 26^0a, the model fit extremely overestimates the response or fails to converge for all other dies. This is believed to be caused by a critical shear stress limit being reached when the contact pressure stress becomes very large. By allowing sliding to occur if the magnitude of the shear stress reaches the critical shear stress limit, regardless of the magnitude of the contact pressure stress, sliding of the dough on the barrel surface would take place and therefore the extrusion pressure would drop. Therefore an alternative contact definition was employed, consisting of a critical shear stress limit, τ_{max}, combined with the coefficient of friction, μ, as mentioned above. This value has not been determined experimentally so far therefore a parametric study was used to derive its value inversely. Examples of the parametric study results are shown in Figure 2 (curves $\mu = 0.09$ with different τ_{max} values) for the low and high extrusion speeds respectively. The value of τ_{max} which leads to agreement between the experimental and numerically predicted values can be obtained and these τ_{max} values for the various dies at 50 mm/min are approximately as follows: 0.3, 0.3, 0.3, 0.5 and 2 kPa for Dies 26^0a, 26^0b, 26^0c, 44^0, and 72^0 respectively. For the higher speeds, the required τ_{max} values are as follows: 0.3, 0.3, 0.3, 2 and 5-7 kPa for Dies 26^0a, 26^0b, 26^0c, 44^0, and 72^0 respectively. Note that for Die 108º, convergence or steady state was not obtained at either speed due to severe distortion of some elements.

Although it is difficult to conclude a trend in the $\tau_{\max}$ value when both imposed strain and strain rate are varying simultaneously, it is apparent that $\tau_{\max}$ increases as strain or strain rate increase. The obtained values seem reasonable in terms of their magnitude but experimental validation through testing of the dough/die wall interface is needed. Also note that this 'critical shear stress' friction model is a different approach from the usual Mooney model; in the latter, wall slip velocities determined from rheological experiments with various capillary dimensions are used as boundary conditions at the wall [9]. Such experiments were not conducted here and it would be interesting to compare the two methods in a future study.

CONCLUSIONS

Extrusion experiments with dies of different entry angles and exit radii were conducted. The dough used in the extrusion experiments was first characterised through mechanical tests including uniaxial tension and lubricated compression, stress relaxation and cyclic loading tests. A non-linear viscoelastic model was calibrated using these mechanical data consisting of a hyperelastic model combined with the Prony series as well the Mullins model. Numerical simulations of the extrusion were then performed, where an adaptive meshing technique was chosen. Simulations performed using a frictionless contact between the billet and die wall showed that the model underestimates the response at high entry angles. Therefore a frictional contact between the die wall and the billet surface was defined, where the kinetic coefficient of friction, μ, of 0.09 was used as measured by Wanigasooriya (2006). When this value of μ was used in the model, the response was overestimated, i.e. the extrusion pressure was much higher than the experimentally measured values. A more realistic contact definition is to impose a limit, $\tau_{\max}$, on the wall shear stress before slip occurs. The results showed that $\tau_{\max}$ varied between 0.3 – 7 kPa depending on the entry die angle (imposed strain) and extrusion speed (strain rate). This suggests complex contact behaviour between die wall and dough, which needs to be investigated further in the future.

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