Rheology of mozzarella cheese: Extrusion and rolling

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Abstract

A capillary rheometer was used to determine the processability and rheology of mozzarella cheese over the temperature range of 25–60°C. End pressure corrections, which are corrections associated with the entry and exit of the mozzarella cheese in and out of the capillary die, were found to be significant. Surprisingly, wall slip was found to be insignificant up to shear stress values of 30 kPa. Capillary extrusion at low temperatures (<50°C) resulted in extrudates that were distorted, while at higher temperatures (>50°C), the extrudates were fairly smooth. Rolling experiments at 25°C indicated that rolling can be used to shape mozzarella cheese (at a reduction ratio <2.1) without fracturing. Based on the extrusion and rolling experiments, mozzarella cheese can be described as a power law fluid with an index of about 0.24, while at higher temperatures (30°C < T < 60°C), the power law index is about 0.4, indicating its increased flowability.

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1. Introduction

Food processing is typically done to increase the shelf life of food products or to add value to food by improving its texture, shape, and overall attractiveness. Value-added products are commercially attractive and allow manufacturers to obtain higher profit margins for their products. One method to process food materials effectively is extrusion. This process is very important because some food product shapes and textures can only be achieved by extrusion (Cheyne, Barnes, & Wilson, 2005; Masi, Cavella, & Sepe, 1998). In addition, extrusion processing increases productivity and reduces production costs (Wiedman & Strobel, 1987).

It was the main objective of this work to explore extrusion in the processing of mozzarella cheese. Emphasis was placed on characterizing processing of the mozzarella cheese using extrusion and rolling. In addition, rheological properties, which play a role in the processability and shapeability of mozzarella cheese, were also of particular interest, together with possible structural and texture changes that may take place during these processes. Understanding the performance of mozzarella cheese during these operations may be beneficial to the dairy industry as they may identify more efficient or more economical alternative ways of continuous processing. While extensive experimental, numerical, and simulation studies exist on the processing of cheddar and gruyere (such as those done on wire cutting of cheese by Goh, Charalambides, & Williams, 2003, 2005), to our knowledge very limited use of capillary extrusion has been made in mozzarella cheese processing and none has been made of rolling.

Capillary rheometers have been widely used to characterize and analyze the processing behavior of molten polymers (Dealy, 1982; Ferry, 1980). Several authors have also used the capillary rheometer to characterize viscoelastic food materials such as dough (Bagley, Dintzis, & Chakrabarti, 1998; Sharma, Hanna, & Chen, 1993; Shukla & Rizvi, 1995) and chocolate (Chen & Mackley, 2006; Ovaici, Mackley, McKinley, & Crook, 1998), due to their similarities to molten polymer. These authors suggest that the end effects in extrusion, which are associated with the excess pressure drop due to the die entrance and the exit flow of the material, are significant and should always be considered when determining the true rheological properties from capillary extrusion experiments. For example, the flow behavior of flour dough was reported to follow a shear thinning model with a power law index of 0.23–0.52

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The effect of the type of material and extrusion operating parameters on the resulting capillary extrudates has also been studied to assess shapeability for chocolate (Chen & Mackley, 2006; Ovaici et al., 1998) and wheat flour dough (Lawton, Davis, & Behnke, 1985).

As already mentioned earlier, the use of capillary rheometry in cheese and processing characterization is limited. Smith, Rosenau, and Peleg (1980) assessed the melt flowability of mozzarella cheese using a capillary rheometer. They found that capillary extrusion can be a suitable tool for characterization of mozzarella cheese. Based on their experimental results, they reported that mozzarella cheese is a Herschel–Bulkley fluid. However, they failed to characterize Cheddar and American process cheeses because these types of material induce serious slippage, which causes significant scatter in the data. Unfortunately, the authors did not present a detailed slip analysis. Smith et al. (1980) also did not present any correlation between capillary rheometrical data and data obtained from other rheometers such as parallel plate or sliding plate. In another report, Taneya, Izutsu, Kimura, and Shioya (1992) used capillary rheometer to study the flow properties of string cheese curd. Although they did not provide a detailed rheological analysis, they observed that the end effects were not negligible and that a slight yield stress was observed at 45°C. At temperatures above 50°C, there seemed to be no yield stress, which led the authors to model the curd as a power law fluid. Currently, extrusion can be used to manufacture string cheese (for example, see Cortes-Martines, Schroeder, Wolfschoon, Schmid, & Mehnert, 2005), but there has been limited research work performed in the extrusion of cheese in general.

Rollers are commonly used in the forming of metals and sheeting of synthetic polymers, processes known as cold or hot rolling and calendaring, respectively. In the food industry, rolling is mostly performed to sheet dough for bread and cookie production. Consequently, experiments on rolling to characterize dough and to model the sheeting process have been done by several authors (Engmann, Peck, & Wilson, 2005; Levine, 1996; Peck, Rough, Barnes, & Wilson, 2006). Rolling of cheese, however, has not been used before as an alternative method of cheese processing.

In this paper, capillary extrusions and rolling experiments are described. Full analysis of the capillary data, including wall slip, was performed to investigate extrusion as an alternative processing method. Structural changes that may occur during these processes were also studied. The results obtained from the capillary rheometer are compared with those obtained from small amplitude oscillatory shear experiments that were presented in our earlier work (Muliawan & Hatzikiriakos, 2007) in order to check the consistency of the results. Processability and shapeability of mozzarella cheese by extrusion and roll forming processes were also assessed together with structural and textural changes that may occur during these processes.

### 2. Experimental

#### 2.1. Materials

Best Buy mozzarella cheese (Lucerne Foods, Calgary, Alta., Canada) was used as the material for this study. Table 1 summarizes the chemical composition of the mozzarella cheese. To assess the consistency of the cheese, before and during the completion of the work, each batch of samples procured was tested for linear viscoelastic properties. It was observed that the differences in the linear viscoelastic properties of the different batches (15 batches) were about ±10%, which is acceptable in a highly heterogenous material such as mozzarella cheese.

#### 2.2. Equipment and methodology

The capillary rheometer used in this work was a constant speed piston driven Instron capillary rheometer (Instron, Norwood, MA, USA). The plunger of the rheometer was capable of traveling at a maximum speed of 85 mm s⁻¹. An 890-N load cell was used to measure the extrusion pressure. The barrel of the rheometer has a diameter of 9.525 mm and an effective length of approximately 305 mm. The barrel was also equipped with PID-controlled heaters that control the temperature within ±0.1°C. Capillary dies of various diameters, entrance angles, and lengths were used as reported in the following text.

Preliminary capillary extrusion tests for the extrusion of cheese following the method typical for polymers (chopped and loaded into the barrel), as suggested by Smith et al. (1980), did not yield a steady-state extrusion pressure. This was mainly due to trapped air in the barrel. An alternative loading method was developed and used in this work. A mold was used to cut a number of cylindrical cheese samples with a diameter slightly less than that of the barrel. A typical cylindrical cheese sample had a diameter of about 9 mm and a length of about 50 mm. These cylindrical cheese samples were inserted (stacked) into the barrel of the

<table>
<thead>
<tr>
<th>Component</th>
<th>Content</th>
<th>Error</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>6.08 (wt%)</td>
<td>–</td>
<td>Calculated⁴</td>
</tr>
<tr>
<td>Fat</td>
<td>25.29 (wt%)</td>
<td>±0.1 (wt%)</td>
<td>AOAC 991.36 (modified⁵)</td>
</tr>
<tr>
<td>Moisture</td>
<td>42.44 (wt%)</td>
<td>±0.1 (wt%)</td>
<td>AOAC 95.46</td>
</tr>
<tr>
<td>Protein-total</td>
<td>22.6 (wt%)</td>
<td>±0.5 (wt%)</td>
<td>AOAC 981.10 (modified⁶)</td>
</tr>
<tr>
<td>Calories</td>
<td>3.42 (kcal g⁻¹)</td>
<td>–</td>
<td>Atwater calculation</td>
</tr>
<tr>
<td>Calcium</td>
<td>7.45 (mg g⁻¹)</td>
<td>–</td>
<td>AOAC 985.35 (modified⁷)</td>
</tr>
</tbody>
</table>

⁴Carbohydrate content approximated as (100–wt% moisture–wt% protein–wt% fat–wt% ash).
⁵Extraction time at boiling was 3.5 h instead of 25 min, drying oven temperature was 100°C instead of 125°C.
⁶Weight of sample was 1.0 g instead of 2.0 g, digestion time was 2.5 h instead of 45 min, acid used for titration was sulfuric acid instead of hydrochloric acid.
⁷Microwave digestion instead of ashing.

(Cuq, Yildiz, & Kokini, 2002; Sharma et al., 1993).
capillary rheometer. The plunger of the capillary rheometer was then allowed to compress the cheese until a pressure of about 0.3 MPa was achieved. At this pressure, the cheese was allowed to rest for about 5 min for thermal equilibration. The pressure was then increased to about 0.5 MPa and maintained for 2 min before the actual extrusion process started. This method proved to be an excellent way of loading the cheese into the barrel of the rheometer and the capillary extrusion runs resulted in consistent steady-state extrusion pressures.

The capillary experiments involved different extrusion speeds using dies of various diameters, entrance angles, and lengths. Experiments were carried out at various temperatures ranging from 25 to 60 °C. The capillary data are presented as wall shear stress in the die, \( \sigma_w \), versus the apparent shear rate, \( \dot{\gamma}_A \). The wall shear stress is calculated from the expression (Dealy & Wissbrun, 1990):

\[
\sigma_w = \frac{P_d - \Delta P_{	ext{ends}}}{4(L/D)}
\]  

(1)

where \( L \) (m) and \( D \) (m) are the length and diameter of the cylindrical section of the die, respectively, \( P_d \) (Pa) is the driving (extrusion) pressure, and \( \Delta P_{	ext{ends}} \) (Pa) is the ends pressure correction. \( \Delta P_{	ext{ends}} \) corrects the measured pressure drop across the capillary die for the excess pressure drop due to the die entrance and the exit flow of the material. This can be obtained from a Bagley plot, which is a plot of extrusion pressure as a function of length-to-diameter ratio, \( L/D \) (constant diameter) at different shear rates. In the Bagley plot, extrapolation of the pressure drops to the values corresponding to a \( L/D \) ratio of zero yields the end pressure corrections for the different shear rates. Alternatively, end pressure corrections can be obtained from capillary extrusions at the same shear rate using a die having a \( L/D \) ratio of about zero (Dealy, 1982). The shear stress calculated without the end pressure correction will be referred to as the apparent wall shear stress, \( \sigma_A = P_d/(4L/D) \).

The apparent shear rate is defined as

\[
\dot{\gamma}_A = \frac{32Q}{\pi D^3}
\]  

(2)

where \( Q \) is the volumetric flow rate (m³). For a Newtonian fluid, this is the true shear at the wall; however, for a non-Newtonian fluid, this is only the apparent shear rate. This apparent shear rate can be corrected to determine the true shear rate at the wall as follows:

\[
\dot{\gamma}_w = \frac{3 + b}{4} \left( \frac{32Q}{\pi D^3} \right) = \frac{3 + b}{4} \dot{\gamma}_A
\]  

(3)

where \( b \) is the Rabinowitsch correction given by

\[
b = \frac{d(\log \dot{\gamma}_A)}{d(\log \sigma_w)}
\]  

(4)

This correction term is a measure of the deviation of a polymeric fluid from Newtonian behavior. It equates to 1 for a Newtonian fluid and \( 1/n \) for a power law fluid.

In capillary extrusion, it is common to observe wall slip at shear stress above a critical shear stress value. Wall slip is a phenomenon in which the material does not adhere to the wall, thus violating the classical no-slip boundary layer. Thus, the apparent shear rate must be corrected for wall slip, if present, to obtain the wall shear rate. To check the occurrence of wall slip, a technique developed by Mooney (1931) was used. Capillaries of different diameters and constant \( L/D \) were used to determine the flow curve of the material under study (\( \sigma_w \) versus \( \dot{\gamma}_A \)). In the absence of slip, the flow curves should be independent of the capillary die diameter. Any dependence of the flow curve on the die radius at a given \( L/D \) ratio implies the existence of slip.

Rolling experiments were also performed as means of further assessing the processability of mozzarella cheese. To our knowledge, there are no reports on the roll forming properties of mozzarella cheese. In our work, rolling experiments were performed using the Sentmanat Extensional Rheometer (SER; Xpansion Instruments, Akron, OH, USA). Descriptions of this rheometer can be found in Sentmanat (2004) and Sentmanat, Muliawan, and Hatzikiriakos (2004); a simple schematic is shown in Fig. 1. The SER is designed to fit into the convective heating oven of a rotational rheometer (Bohlin VOR, Malvern Instruments, Westborough, MA, USA), so that measurements can be performed at elevated temperatures. However, since the rolling experiments were

![Fig. 1. Schematic of the setup for the rolling experiment using the Sentmanat Extensional Rheometer (SER).](image-url)
performed at ambient temperature (around 25°C), no temperature control was utilized. The gap between the drums/rollers of the SER is fixed at a distance of 0.241 cm, thus samples with different thickness were prepared to achieve different reduction ratios (the ratio of the sample thickness to the size of gap between the rollers). Samples with average thickness of 5.48, 5.14, 4.20, and 3.40 mm were used to achieve reduction ratios of 2.3, 2.1, 1.7, and 1.4, respectively. The rolling samples had different widths (~5 to ~12 mm), so that we could have control of the contact area between the sample and the rollers, and thus to ensure that the rolling experiments were operated within the acceptable range of operation of the torque transducer of the rheometer. The sample with the smallest thickness would be the widest and vice versa. Six different linear roller speeds were used in these experiments. The steady thickness of each sample after it had passed the rollers was also measured and recorded. Exit thickness value is the average of measurements done at three different positions on the sample. The recovery in thickness can be used as a measure of elasticity, i.e., the ability of the material to store energy when it passes through the rollers, which is then released and manifests itself as recovery in thickness.

The shear force on each roller can be calculated from the total torque of the rheometer as follows:

\[ F_S = \frac{T}{2R} \]  

where \( F_S \) is the shear force (N), \( T \) is the torque (N m), and \( R \) is the radius of the roller (m) (Fig. 1). However, since the area of contact between the sample and the rollers is different for each run, it is proper to normalize the shear force by the area of contact to obtain the shear stress:

\[ \sigma_S = \frac{T}{2RA} \]  

The area of contact was calculated based on the arc that was formed by the angle, \( \theta \), as illustrated in Fig. 1.

Finally, microscopic images were produced to identify visually any structural changes that occurred within the cheese after extrusion and roll forming. This was achieved using a cryo-scanning electron microscope (SEM; Hitachi S4700 SEM with Emitech K1250 Cryo System, Pleasanton, CA, USA). The samples collected for imaging were stored in an airtight container before their microscopic images were taken and all microscopic images were taken within 24 h. Before imaging, the samples were flash frozen using liquid nitrogen and they were fractured to expose the internal surface. The microscopic images are taken at random locations within the extruded and rolled samples and only representative images are shown.

3. Results and discussions

3.1. Linear viscoelastic measurements

Linear viscoelastic properties of the mozzarella cheese were determined previously (Muliawan & Hatzikiriakos, 2007).

The time temperature superposition principle was successfully applied on the linear viscoelastic data obtained at 40, 50, and 60 °C. However, data obtained at 25 °C were not able to be included in the superposition. This failure of time temperature superposition was attributed to the fact that the mozzarella cheese underwent physical changes (melting) and is a multiphase system over the temperature span of 25–40 °C, where protein, moisture and solid and liquid fat co-exist. The different system constituents exhibit relaxation behaviors that have different temperature dependence. For more details on this result, readers are referred to our other publication (Muliawan & Hatzikiriakos, 2007).

3.2. Capillary extrusion and flow curve

Capillary extrusion experiments were performed at 25, 40, 50, and 60 °C. Typical pressure transients obtained from the capillary rheometer are shown in Fig. 2. The variance of the steady-state extrusion pressure was significant in some cases, as typically expected in the testing of food materials such as cheese (Cheyne et al., 2005). In the present case, the standard deviation of the steady-state value for most cases was about ±8%. The variation was due to the heterogeneity of the sample and the way the sample extruded. It was observed that the sample did not extrude smoothly, but rather exhibited a stick-slip type of extrusion, particularly at the lower and higher ends of the experimental range of shear rates. This behavior was also persistent at low temperatures where the cheese exhibits a certain degree of solid-like behavior. Extrusions results plotted in Fig. 2 are averages of multiple runs and the standard deviations of these replicates are within ±15%. This allows a meaningful flow curve for mozzarella cheese to be obtained.

Fig. 3 depicts the apparent flow curves of cheese at 25 °C obtained from three dies each having a diameter of
0.43 mm, and an entrance angle of 180°, but different length-to-diameter ratios, L/D, of 15, 30, and 47. Lack of superposition of the data is due to the fact that the shear stress has not been corrected for the ends pressure as discussed earlier. This is done by constructing a Bagley plot (Fig. 4), where the extrusion pressure is plotted as a function of L/D for several apparent shear rate values. A linear relationship between the extrusion pressure and the L/D was observed. This shows that pressure and viscous heating have no significant effect on the viscosity of the sample, although these have opposite effects in a Bagley plot and can eliminate each other (Rosenbaum & Hatzikiriakos, 1997). Extrapolation of the straight lines to zero L/D results the end pressure, ΔP_{ends}, and thus the true shear stress can be obtained from Eq. (1). It is noted that the Bagley correction can be significant. For example, at the shear rate of 38 s^{-1}, the end correction accounts for as much as 26% of the total extrusion pressure.

The Bagley-corrected flow curves of mozzarella cheese for various L/D are shown in Fig. 5. All flow curves for the three different dies of various L/D ratios fall on a single line, defining uniquely the apparent flow curve of the mozzarella cheese at 25 °C. Each of the apparent flow curves in Fig. 5 exhibits a slope of about 0.24, which translates to a Rabinowitsch correction (Eq. (4)) of 4.1. This correction is used to generate the true flow curve of mozzarella cheese, which is shown in Fig. 6. In this figure, the true (Bagley and Rabinowitsch corrected) flow curves of the mozzarella cheese at 40, 50, and 60 °C are also plotted (at these relatively higher temperatures, the Rabinowitsch corrections are found to be 2.7, 2.4, and 2.4 for 40, 50, and 60 °C, respectively). The slope at 25 °C, as indicated earlier, is 0.24 (σw = K_0^{0.24} with K = 4.7 Pa) which is significantly different from those at the higher temperatures (~0.40). This is due to the different nature (structure) of cheese at low temperature (solid-like) compared with that at higher temperatures (liquid-like), as previously illustrated (Muliawan & Hatzikiriakos, 2007).

### 3.3. Wall slip

To determine possible wall slip effects, the true flow curves of the material obtained using dies with various diameters are needed. Referring to Fig. 6, it can be seen that, at 25 °C, the flow curve of mozzarella cheese is independent of the die diameter, and therefore no slip effects are present in capillary extrusion up to wall shear stress values of about 30 kPa. This value is perhaps too low
For example, at 60°C (see Fig. 8). At 60°C, cheese is in a molten state, and there is an absence of yield stress, which should induce capillary flow readily, even at relatively low shear rates (Muliawan & Hatzikiriakos, 2007). The absence of yield stress was also identified as the reason for the agreement between the steady and dynamic viscosities at 60°C (Muliawan & Hatzikiriakos, 2007).

3.4. Extrudate appearance

Typical extrudates collected from the extrusion experiments are shown in Fig. 7. The extrudates were obtained from the extrusion of the cheese sample at 25°C using a die with a diameter of 0.813 mm, L/D of 15, and entrance angle of 180°. These pictures were taken using an optical microscope (Olympus Mic-D, Olympus, Center Valley, PA, USA). Surface defects appear even at very small shear rate values. At such relatively low temperature, the mozzarella cheese retains its solid-like behavior and tends to fracture as it extrudes. Surprisingly, the surface of the extrudates improves as the shear rate increases. A possible explanation is that the extrusions at relatively high shear rates may generate shear heating sufficient to cause the cheese in contact with the die wall to melt locally and flow as illustrated in the extrusion at relatively high temperatures. For example, at 60°C, the extrudates all show a relatively smooth surface (even for shear rate as low as 27 s⁻¹) (see Fig. 8). At 60°C, cheese is in a molten state, and during extrusion, it flows instead of fractures, which results in a defect-free extrudate surface. Furthermore, it has also been reported that, at 60°C, there is an absence of yield stress, which should induce capillary flow readily, even at relatively low shear rates (Muliawan & Hatzikiriakos, 2007). The absence of yield stress was also identified as the reason of the agreement between the steady and dynamic viscosities at 60°C (Muliawan & Hatzikiriakos, 2007).

3.5. Effects of die geometry

Dies of different entrance angles were also used to extrude the cheese. The apparent shear stress, \( \dot{\gamma}_A \), is depicted as a function of the contraction angle, \( 2\alpha \), for several values of the apparent shear rate, \( \dot{\gamma}_A \), in Fig. 9. There seems to be an optimum value of entrance angle at which the wall shear stress is minimized. This trend has also been observed in the extrusion of polytetrafluoroethylene paste, where it was found that at sufficiently small entrance angle, the flow of the material in the die conical section follows a plug flow type of pattern known as “radial flow” (Ariawan, Ebnesajjad, & Hatzikiriakos, 2002). The decrease of the apparent shear stress at small entrance angles is consistent with the lubrication approximation for flow of molten polymer and other materials (Dealy & Wissbrun, 1990). The slight increase in the apparent shear stress beyond a certain entrance angle (30°) is also consistent with the trends observed in the extrusion of elastic solids (Ariawan et al., 2002; Horrobin & Nedderman, 1998). Although this set of experiments was performed only at a temperature of 25°C, it is expected...
that at higher temperatures, where the flow properties of the mozzarella cheese are similar to those of molten polymer, the effect of die geometry on the flow curve will exhibit a similar trend. In terms of extrudate appearance, however, it appears that the entrance angle of the die does not seem to have any significant effect. Furthermore, extrusions using dies with different lengths and diameters have shown that these geometrical characteristics have no significant effect on the extrudate appearance.

3.6. Roll forming of mozzarella cheese

Rolling experiments were performed at 25 °C. Similar to the extrusion experiments, the variance of the steady-state rolling force is significant in some cases. In this case, the standard deviation of the steady-state value for most cases can be as high as ±20%. Peck et al. (2006), in their rolling experiments on flour dough, observed data variation of about 17%. Thus, it appears that such variation is typical in food materials where sample heterogeneity can be significant. To minimize the effect of these variations, replicates of at least four runs were performed to generate the rolling curves.

The rolling shear stress as a function of the roller linear speed for different reduction ratios is shown in Fig. 10. The rolling shear stress and the linear speed of the roller follow a power law relationship for a given reduction ratio value. Increase in roller speed results in an increase in shear stress. The rate dependence can be represented with a power law index of 0.26, 0.27, 0.28, and 0.25 for the reduction ratios of 1.4, 1.7, 2.1, and 2.3, respectively. These values compare well with the slope of the flow curve obtained from the capillary extrusion experiments at 25 °C. Roughly speaking, dividing the roller speed by the distance between the rollers results in a characteristic shear rate, and thus such agreement is not surprising. Furthermore, these values appear to be in good agreement with those observed in the rolling of bread dough (Engmann et al., 2005). A higher reduction ratio also results in a higher rolling shear stress due to the higher extensional strain rate required to roll the cheese into the gap. The shear stress appears to increase with the reduction ratio exponentially, which is in agreement with the rolling of soft and hard flour doughs at comparable reduction ratios (Peck et al., 2006).

The thickness of the sample as it exits the rollers was also measured in order to determine the elastic recovery of the material. The rolled samples were allowed to relax fully...
before the thickness was measured using a caliper. Fig. 11 shows the recovery of thickness (exit thickness/roller gap) as a function of the roller speed for different reduction ratios. For a constant reduction ratio, the thickness recovery of the sample increased with roller speed. Thus, samples that were rolled at higher roller speed experienced a higher degree of swelling. It can also be seen that for a reduction ratio of 2.3, the reduction in the thickness of the samples can be quite significant (as high as 22% of the initial sample thickness). It must also be noted that the standard deviation of the measurements at the reduction ratio of 2.3 was relatively higher than the standard deviations obtained at lower reduction ratios. This is because the deformation at such reduction ratio is quite significant, which causes the sample to fracture. In general, however, the cheese was able to be rolled cleanly, without any significant adherence of the cheese on the rollers. Thus, rolling seems to be a viable option to shape mozzarella cheese as long as the reduction is kept relatively small (<2.1) to maintain the structure and appearance of the cheese.

3.7. Microscopic images

Fig. 12(A) depicts cryo-SEM pictures of the internal structure of the mozzarella cheese that does not undergo any testing. It can be seen that unprocessed cheese has a structure that is mostly made up of protein matrix with dispersed fat globules. Fig. 12(B) shows the microscopic image of a cheese extrudate, which was obtained from extrusion experiment at 25°C. Extrusion seems to have destroyed the fat globules or forced the fat to exude to the surface. The cryo-SEM of the extruded mozzarella cheese also reveals how the protein matrix was disrupted, causing sharp ridges to appear, illustrating the large-scale deformation imposed by the capillary rheometer. Fig. 12(C) and (D) show the microscopic images of cheese samples that were rolled under different rolling conditions. It can be seen that rolling had minimal effect on the structure of these cheese, essentially preserving their morphology.

4. Conclusions

Rheological and processing characterization of mozzarella cheese was performed using a capillary rheometer. While end pressure corrections were successfully applied to generate the true rheological properties of the mozzarella cheese, wall slip was found to be insignificant under the experimental conditions used. Visual observations of the extrudates obtained from capillary extrusions experiments indicate that extrusion can be used to shape mozzarella cheese with smooth profiles at relatively high shear rates or at a temperature where the cheese is in molten state. This opens up the possibility of efficient manufacture of mozzarella cheese with shapes that are commercially attractive. It was also found that there is a minimum in the extrusion pressure of the mozzarella cheese at an optimum die entrance angle (30°).
Rolling experiments were also performed in this work. It was found that rolling experiments can provide additional insight on characterizing processability of the mozzarella cheese. It was observed that rolling can be used to shape mozzarella cheese provided that the reduction ratio is kept at low levels (<2.1). The study performed in this work suggests that extrusion and rolling processes are feasible processing techniques for mozzarella cheese. Future work can include a feasibility study on the hot rolling of mozzarella cheese. We believe that a much higher reduction ratio can be achieved at relatively higher temperatures, where the cheese is in a molten state.

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References