The optimization of the Extrusion conditions on Hardness of Butter using response Surface Methodology

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Abstract

Bulk butter was subjected to reworking by a co-rotating twin-screw extruder. Extrusion process effectively improves the work softening of butter. In the present work, the effects of extrusion conditions such as screw speed, feed rate and feed temperature on the hardness and work softening of the extruded butter were investigated. A central composite rotatable design (CCRD) was used with Three controlled variables: screw speed (50, 100, 175, 250 and 300 r/min); feed rate (20, 30, 45, 60 and 70 kg/h) and feed temperature (5, 7, 10, 13 and 15c˚). The experimental values of the work softening measured from 57.44 % to 47.11%. A second-order model was obtained to predict the work softening. It has been found that screw speed and feed rate had significant effect on work softening, which increased with increasing the experimental independent variables. Optimum processing condition generated from the models was: Hardness 14.59 (kg/cm2) and work softening 67.28 %. The predicted responses in terms of screw speed, feed rate and feed temperature were 221.48 r/min, 36.16 kg/h and 11.41 C, respectively. The predicted values registered non-significant ($p < 0.01$) difference from experimental values.

Keywords: butter; Extrusion; work softening; Response surface methodology

1. Introduction

Butter production is linked to cream availability on a worldwide basis and hence is difficult to synchronize with consumer demand. Storage and transportation requirements favour bulk packaging. These bulk packs must be stripped and the butter reworked as a preliminary to packing for retail sale, when a sell-by date has to be declared on each pack.

The major effect of reworking is to disrupt the fat crystal matrix formed during storage of the butter, a process known as work softening. (Gonzalea and Andrew, 2000).

This step also helps to disperse the water and salt in the continuous oil phase and promotes the release of fat crystals and oil from the fat globules (Boudreau and Saint-Amant, 1985). Reworking can be used to reduce butter hardness (MacGibbon and McLennan, 1987). Although softening occurs, some of the original Warmness is regained during storage because of thixotropic setting (DeMan, 1976). Beyond a certain point, working has no effect on butter hardness. With excessive working, however, Butter can become sticky (Sone et al., 1966; Gupta and deMan, 1985).

During mechanical treatment, a hardness reduction occurs which is partly permanent and partly reversible.It has been that the crystal network structure in plastic fats contains bonds of two types: those that reform after mechanical disturbance and those that do not reform (Van den Tempel, 1958; DeMan and Wood, 1958)

The exact nature of the changes that take place during the mechanical disturbance of a plastic fat is not known (Voisey et al., 1966).

Optimum reworking conditions have been found to vary considerably with the type of butter being processed (Gallat et al., 1996).

The rheological considerations used in estimating the conditions in the extruder can also be applied to the reworker. Therefore determination of these variables in characterization of the final product is very important.

However, the effect of Different extrusion condition on the hardness of butter is still lacking. This project focuses on the work softening changes during extrusion of butter.The intraction of variables (screw speed,feed rate and feed temperature) had been studied using RSM, in order to optimize the processing condition to achieve the best work softening.

2. Materials and method

2.1. Materials

Bulk butter (Fonterra Brands, Auckland, New Zealand), was supplied by Razavi Butter packaging plant, Mashhad, Iran and transferred chilled to the Iranian academic center for education culture and research (Mashhad, Iran) and was divided into five parts. Each of them stored in certain temperature (5, 7, 10, 13 and 15c) to achieve the desired temperature in extrusion process.

2.2. Experimental design

The effects of Three independent extrusion parameters (variables) screw speed (X_1), feed rate (X_2),feed temperature(X_3) on the work softening (dependent variable)were investigated using central composite rotatable design (Yuan & Zhou, 2000) and RSM. All variables were controlled at five different levels. A second-order polynomial equation was then used to fit the measured, dependent variable (Y) as a function of the coded, independent extrusion variables (x).

The model proposed for a response Y writes

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ij} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} x_i x_j \qquad (1)$$

Where Y is the measured response variable (Work softening), β_0 is a constant, βi is the linear coefficient (main effect), β_{ij} is the quadratic coefficient, x_i and x_j are independent variables.

2.3. Extrusion and sample preparation

A Chaina SLG67-18.5 co-rotating twin-screw extruder with the length-to-diameter ratio of 27.9:1 and screw diameter of 47 mm was used in the present study. A circular die of 5.2 mm diameter was used.

The extruder was equipped with a pre-calibrated Rospen twin-screw volumetric feeder (Gloucestershire, UK) was used to control the butter inputs respectively.

A total of 20 extrusion processes with different independent variable combinations has been carried out in the following range: screw speed (50–300 r/min), feed rate (20–70 kg/h) and feed temperature (5–15 C).

The extrudates were cooled down to 5c and packed in polyethylene cups before the hardness measurements.

2.4. Determination of work softening

Penetrometer hardness was measured according to AOCS method Ce 16-60 , and results were reported in 0.1 mm as well as in kg/cm 2 as proposed by Vasic and deMan (1967). Work softening was calculated from

$$WS = \frac{H_0 - H_W}{H_0} \times 100 \qquad (2)$$

where Ho and Hw represent the hardness of the unextruded and extruded samples, respectively. Each test was repeated 3 times.

2.5. Statistical analysis

Response surface methodology (RSM) with central composite rotatable design was employed to investigate the effect of Extrusion conditions on hardness of butter. Three independent parameters namely, screw speed, feed rate and feed temperature at five different levels each, were employed. The parameters chosen and their levels were based on preliminary experiments carried out in our laboratory. The experimental plan was designed and the results obtained were analyzed using Design Expert version 8.0.7.1 (Stat-Ease Inc., Minneapolis, MN) software to build and evaluate models and to plot the three-dimensional response surface curves. For this study, a total of 20 experiments were carried out. The experimental design consisted of one factorial point, one extra point (star point) to form a central composite rotatable design and six replicates for the center point. Optimization was performed using a rotatable CCD with an alpha value of ±1.682 for three factors. The experiments were run in random order to minimize the effects of unexpected variability in the observed responses due to extraneous factors.

2.6. Optimization

Optimum values of the processing variables were obtained with the help of the numerical optimization technique of the Design-Expert software (Design Expert ver. 8.0.7.1). The software necessitates assigning goals to the processing variables and the responses. All the processing variables were kept within range while the responses were either maximized (work softening) or kept in minimized (Hardness). In order to search a solution satisfying the imposed constraints, the goals are combined into an overall composite function, D(x), called the desirability function (Myers and Montgomery, 2002), which is defined as:

$$D(X) = (d_1 \times d_2 \times ... \times d_n)^{1/n} \quad (3)$$

The numerical optimization finds a point that maximizes the desirability function. The characteristics of a goal may be altered by adjusting the weight or importance of specific Variables (Design Expert Version, 2002).

3. Results and discussion

3.1. Experimental results

Table 2 shows the experimentally measured and the regression model predicted work softening. The measured work softening values of the present extruded butter for the 20 combinations of three independent variables (i.e. screw speed, feed rate and feed temperature) fall in the range from 57.44 % to 47.11%. These values are comparable to the work softening values measured from other materials. Using the same work softening determination method, the work softening of lard, margarine and shortening was detected to be between 59% and 62% (VASIC and deMan, 1967). The independent and dependent variables were analyzed to obtain a regression equation for the work softening (Y) which writes

$$Y = 65.48 + 1.86x_1 - 1.40x_2 + 0.95x_3 + 0.26x_1x_2 + 0.26x_1x_3 - 2.14x_2x_3 - 1.26x_1^2 - 1.07x_2^2 - 1.33x_3^2$$

(4)

Table 1 shows that the work softening Values predicted from Eq. (3) compared well with experimental values, with the coefficient of determination R 0.825.

The statistical analysis data (Table 2) shows that the linear and quadratic terms are more significant while some of the interactions less. The response variable (work softening) depends more on the individual change of the independent variables rather than their interaction. It is noticed that there was a moderate lack of fit (P> 0.05), indicating the applicability of the model.

Table 1

Experimental design for the work softening of extruded butter with respective coded factors, variable levels and response function (Y)

Treat ment	Coded variables			Uncoded variables			Hardness (kg/cm2)	Work softening (%)
	Z1	Z2	Z3	screw speed(r/min)	Feed rate(kg/h)	Feed temperature(c)		Experi mental
1	-1.682	0.000	0.000	48.87	45.00	10.00	18.9	58
2	-1.000	1.000	-1.000	100.00	60.00	7.00	17.7	60.66
3	-1.000	1.000	1.000	100.00	60.00	13.00	19.1	57.5
4	-1.000	-1.000	-1.000	100.00	30.00	7.00	18.7	57.44
5	-1.000	-1.000	1.000	100.00	30.00	13.00	15.6	65.33
6	0.000	0.000	0.000	175.00	45.00	10.00	14.9	66.88
7	0.000	0.000	0.000	175.00	45.00	10.00	14.7	67.11
8	0.000	0.000	0.000	175.00	45.00	10.00	16.3	63.77
9	0.000	0.000	0.000	175.00	45.00	10.00	14.8	67.11
10	0.000	-1.682	0.000	175.00	19.77	10.00	15.2	66.22
11	0.000	0.000	0.000	175.00	45.00	10.00	16.4	63.55
12	0.000	0.000	0.000	175.00	45.00	10.00	16.02	64.4
13	0.000	0.000	1.682	175.00	45.00	15.05	16.77	62.73
14	0.000	1.682	0.000	175.00	70.23	10.00	18.4	59.11
15	0.000	0.000	-1.682	175.00	45.00	4.95	17.5	61.11

16	1.000	-1.000	1.000	250.00	30.00	13.00	15	66.66
17	1.000	-1.000	-1.000	250.00	30.00	7.00	17.6	60.88
18	1.000	1.000	-1.000	250.00	60.00	7.00	16.8	62.66
19	1.000	1.000	1.000	250.00	60.00	13.00	16.93	62.37
20	1.682	0.000	0.000	301.13	45.00	10.00	15.2	66.22

Table 2

Analysis of variance (ANOVA) of independent variables for extrusion optimization of butter

Source	Sum of Squares	df	Mean Square	F Value	p-value Probe > F
Model	177.80	9	19.76	6.84	0.0030
A-screw speed	47.48	1	47.48	16.44	0.0023
B-feed rate	26.65	1	26.65	9.23	0.0125
C-Feed temperature	12.27	1	12.27	4.25	0.0662
AB	0.55	1	0.55	0.19	0.6715
AC	0.072	1	0.072	0.025	0.8775
BC	36.64	1	36.64	12.69	0.0052
A^2	22.93	1	22.93	7.94	0.0182
B^2	16.35	1	16.35	5.66	0.0387
C^2	25.43	1	25.43	8.81	0.0141
Residual	28.88	10	2.89		
Lack of Fit	13.79	5	2.76		
Pure Error	15.09	5	3.02		
Cor Total	206.67	19			

3.2. Analysis using RSM

In the present work, the optimum conditions for the maximum work softening were established by fixing three variables at coded zero level (Table 1).

Fig. 1 shows the change of work softening value of the extruded butters with the feed rate and screw speed as predicted from Eq. (2), while the feed rate and screw speed were set at zero level, i.e. 45 kg/h and 175 r/min, respectively. The maximum predicted work softening can be found with the feed temperature of 10c. The work softening value increases with screw speed. This agrees with previous study where the work softening was increased at increasing the speed of the propeller up to 100 r.p.m (DeMan, 1969). This behavior could be explained that during the reworking process there will be both the breakup of the three-dimensional crystal network within the butter and a reduction in the size of the constituent milk fat crystals. With the breakdown of the matrix, further shear brings about reduction in the size of crystals, aggravated by some melting of crystals as the butter warms up. Reduction in the proportion of solid fat would further weaken the structure (Gonzalea and Andrew, 2000).

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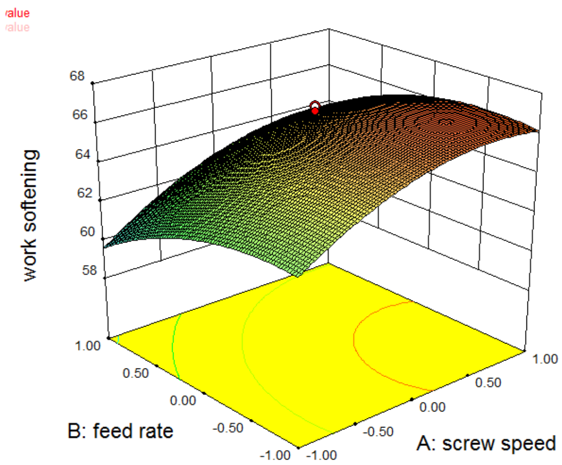

Fig. 1. Effect of screw speed and screw speed on work softening of extruded butter with feed temperature of 10C.

Fig. 2 shows that, when the feed rate content is at zero level of 45 kg/h, the maximum predicted wok softening value can be found at a screw speed of 175 r/min and feed temperature of 10C. The high work softening values are located at feed temperatures about 10C, i.e. the zero level. By increasing the temperature, a less dense fat crystal network would be and there by a more liquid fat area was seen in the system. Liquid fat in the system hinders the interactions between crystals; consequently weaker links are formed (Gonzalea and Andrew, 2000). When crystals and crystal clusters are not connected to neighboring clusters, or if they form weaker links between each other, they are not included in the crystal network, and they do not contribute to the mechanical properties of the fat-based product (Herrera and Hartel, 2000 and Marangoni, Tang DM, 2008). In other words, a thinner network and weak links between crystals lead to a lower hardness.

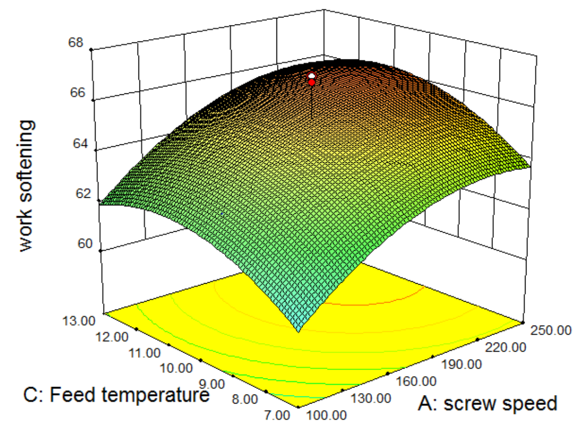

Fig. 2. Effect of screw speed and feed temperature on work softening of extruded butter with feed rate of 45kg/h.

When the screw speed is fixed at 175 r/min, the maximum predicted work softening can be achieved at feed rate of 45kg/h and feed temperature of 10C (Fig. 2).

Similar to that in Fig. 2, high work softening values are located at the feed rate close to the zero level. It has been reported that During the continuous operation of the butter reworker, the flow can be considered in steady state and the shear rate (also called strain rate) may be defined as the rate of change of strain: Since the flow rate was very low in relation to the cross-sectional area of the reworker and the butter viscosity relatively high, the system was working in laminar flow. However, the value of shear rate alone cannot be representative of the reworking conditions because it has been reported that the characteristics of the butter are time-dependent when exposed to a fixed shear rate. Therefore, it is likely that the change in the structure of the butter varies according to the exposure time (Gonzalea and Andrew, 2000).

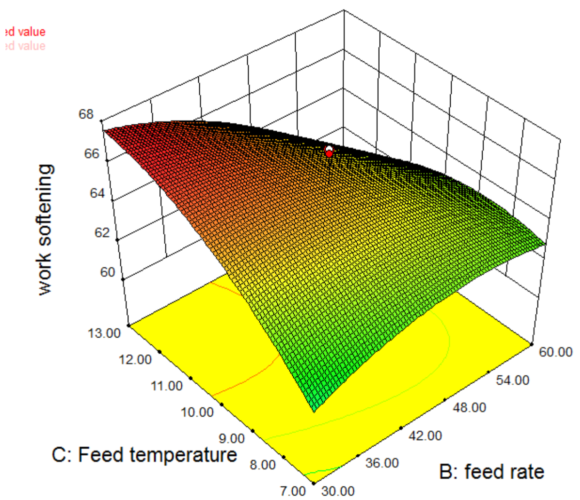

Fig. 3. Effect of feed rate and feed temperature on work softening of extruded butter with screw speed of 175 r/min.

The results indicate that both increasing the screw speed and feed rate increase the work softening significantly.

The result shows that the high work softening values appear at feed temperatures about its zero level, consistent with that in Fig. 3.

A slight increase of the work softening can also be observed with the increasing feed temperatures. But in general, effect of feed temperature on work softening is non-significant that Our are consistent with those of DeMan (1969) indicated that there was little or no difference in final hardness between samples worked at 4 or 15 "C and stored at 15 "C. These experiments indicate that a similar work softening can be obtained over a relatively wide temperature range.

Considering all the results, it was evident that screw speed ($P < 0.01$) and feed rate ($P < 0.05$) had significant effects on the work softening whilst the feed temperature were more limited. The final predicted minimum hardness of extruded butter, which was calculated by Penetrometer, was obtained with 175 r/min screw speed, 45 kg/h feed rate, 10C feed temperature. It should be noted that only the work softening has been considered in the present study. The effects of extrusion conditions on other Parameters, such as Adhesiveness and cohesiveness, have not been considered.

3.3.Optimization and model verification performance

Numerical optimization of the process variables was carried out with the help of commercial software (Design Expert Version, 2002). The optimization was carried out under certain applied constraints. The software was used to generate optimum processing conditions and to predict the corresponding responses as well. The applied constraints and the predicted optimum values obtained for the various responses are reported in Table3 Butter Extrusion was carried out under the optimum processing conditions and the responses were recorded (mean of 5 measurements). The veracity of values of the responses predicted by the software was ascertained with the help of a two-tailed, one sample t-test Table4 The results of the t-test demonstrated no significant difference between the values of the predicted responses and the recorded response. Thus, establishing the suitability of the models to predict the various responses as desired for a particular application.

Table 3

Applied constraints to obtain optimized values of processing variables and the predicted responses.

Variables	Condition	Lower limit	Upper limit	Importance(a)	Optimum value(b)
Screw speed	In range	100	250	3	221.48
Feed rate	In range	30	60	3	36.16
Feed temperature	In range	7	13	3	11.41
			Responses		
Harness	Minimize	14.7	19.1	3	14.59
Work softening	Maximize	57.44	67.11	3	67.28

(a)The value of importance is as per the default setting of the software
(b) The desirability for this result was 1.

Table 4

Results of the t-test conducted to compare the predicted and the experimentally recorded values.

Response	Predicted value(a)	Actual value ±SD	Standard error	% Variation	Mean difference	Significance
Hardness	14.59					
Work softening	67.28					

$$H_{\circ} : \mu_{\circ} = \eta_1, t_{cal} \langle t_{table} at...p \langle 0.1, (H_{\circ}) was...accpted$$

(a) Mean of five replications.

4. Conclusion

Butter was extruded using a co-rotating twin-strew extruder using 20 combinations of screw speed, feed rate and feed temperature. The experimental value of measured work softening varies between 47.11% and 57.44 %. A second-order model developed for the work softening prediction exhibits a non-significant value for lack of fit (P > 0.05) and a high value for the coefficient of determination (R = 0.860). The surface response graphs show that the maximum work softening was obtained at the extrusion condition of screw speed of 175 r/min, feed rate of 45 kg/h and feed temperature of 10C.

Optimum processing conditions and the corresponding predicted response could be obtained with the help of the models. The predicted response at optimum conditions had non significant difference from the experimental values.

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