Characteristic Coloring Curve for White Bread during Baking

Masanobu Onishi,1,∗ Michiko Inoue,2 Tetsuya Araki,2 Hisakatsu Iwabuchi,1 and Yasuyuki Sagara3

1San-Ei Gen F.F.I., Inc., 1-1-1 Sanwa, Toyonaka, Osaka 561-8588, Japan
2Department of Global Agricultural Sciences, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
3Food-Kansei Communications Corp., 4-24-7-103 Sendagi, Bunkyo-ku, Tokyo 113-0022, Japan

Received August 3, 2010; Accepted November 17, 2010; Online Publication, February 7, 2011
[doi:10.1271/bbb.100558]

The effect of heating conditions on the crust color formation was investigated during the baking of white bread. The surface temperatures were monitored with thermocouples attached to the inside surface of the loaf pan cover. The trace of the surface color in the L*a*b* color coordinate system is defined as the characteristic coloring curve. The overall baking process was classified into the following four stages based on the characteristic coloring curve: i) pre-heating (surface temperature < 110 °C), ii) Maillard reaction (110–150 °C), iii) caramelization (150–200 °C), and iv) over-baking (surface temperature > 200 °C). A linear relationship was observed between the L* value decrease and the increase in weight loss of a sample at each oven air temperature. The L* value appeared to be suitable as an indicator to control the surface color by baking conditions.

Key words: characteristic coloring curve; L*a*b* color value; weight loss; surface temperature; white bread

The bread-making process can be broadly classified into mixing, fermentation, molding and baking. Baking, in particular, is a key step in which the raw dough piece is transformed into a light, porous, readily digestible and flavorful product under the influence of heat.1) Numerous studies on bread baking have therefore already been reviewed.2–6) White bread is one of the most popular types, and is distinguished by having a crunchy and yellow-gold crust, besides other features (i.e., a spongy and light crumb with soft texture and intermediate moisture, and a typical flavor).7) White bread (Pullman type) has been extensively adopted in North America and such Asian countries as Japan and South Korea.8) The bakery industry in these countries consequently requires tools to evaluate processing options in the feasibility phase of process design for white bread. Predicting and controlling the development of crust color are particularly important issues for bread-making companies to satisfy consumer preference.9) Surface color is one of the important characteristics of baked products which may be considered as a critical index of baking.10) Bread color develops late in baking, simultaneously with crust formation, and arises from such chemical processes as the Maillard reaction and sugar caramelization.11) The Maillard reaction is mainly responsible for color development at the surface temperatures of bakery products below 150 °C, while caramelization and carbonization occur when the product surface temperature is above 150 °C.12)

Expressing the changing pattern of surface color in an easily understandable manner would be helpful for bakeries to predict the surface color under various heating conditions. However, the relationships among the color values, surface temperature and weight loss of white bread during baking have not previously been systematically investigated.

The objectives of this present work are to measure the changes in the temperatures of white bread samples at the surface during baking and in the color values around the measuring locations of these temperatures, and to define the characteristic coloring curve for white bread during the baking stages based on the relationship among the color values.

Materials and Methods

Sample preparation. Bread dough samples were prepared by using a standard recipe for Pullman-type bread: 100.0 g of wheat flour with an ash content of 0.37% and protein content of 11.8% (Nissin Flour Milling, Tokyo, Japan), 68.0 g of water, 5.0 g of sugar, 5.0 g ofshortening (Nippon Flour Mills Co., Tokyo, Japan), 2.2 g of yeast (Oriental Yeast Co., Tokyo, Japan), 2.0 g of salt, 2.0 g of skim milk powder and 0.1 g of improver (Kim Kyowa Foods Co., Tokyo, Japan) per 100.0 g of flour. The samples were produced by a laboratory sponge-and-dough procedure with formulation and processing conditions similar to those used in Japan (Fig. 1). The sponge ingredients were 70% of the wheat flour, yeast and water, and these were mixed with a 5DM-1-03-R versatile mixer having a 4.5-L container (Dalton Co., Osaka, Japan) for 2 min at 63 rpm and then for 2 min at 126 rpm, before fermenting for 240 min at 29 °C and relative humidity of 85% in a PET-22D fermentation cabinet (Fujisawa Maruzen Co., Tokyo, Japan). The sponge and remaining wheat flour, salt, sugar and skim milk were then mixed for 2 min at 63 rpm and then for 2 min at 126 rpm, before adding shortening and mixing for 2 min at 63 rpm and then for 6 min at 126 rpm. After a 15-min rest period, the dough samples were divided into 360-g portions, rounded, and rested for a further 25 min at 26 °C, before each was loaded into a Pullman loaf pan (80 × 80 × 170 mm, iron-aluminum). After a final proofing for 40 min at 38 °C and relative humidity of 85%, each portion, whose initial moisture content was 47.1% and initial weight was 360 g, had swollen to reach about 2–4 cm beneath the top cover, and was ready for the baking tests.

∗ To whom correspondence should be addressed. Tel: +81-6-6333-0521; Fax: +81-6-6333-3531; E-mail: moomisi@saneigenffi.co.jp
Baking tests. The dough samples were baked in a DOE-02 static electric oven (Misuzu Koki Co., Mie, Japan) with oven air temperatures ranging from 140 to 260°C and baking times from 5 to 80 min. A jack stand was placed in the center of the oven to ensure uniform heating conditions. The results of preliminary experiments showed that all of the bread loaves on a jack stand had been baked under the same thermal conditions.

Measurement of the temperature and weight loss. As shown in Fig. 2, the top surface temperatures of the sample were measured by using five sheathed thermocouples attached to the inside surface of the loaf pan cover. These thermocouples were of the K type comprising chromel-alumel wires of 0.2 mm in diameter. The oven air temperature \( T_{\text{air}} \) is defined as that measured with another thermocouple whose junction was located 10 mm above the center of the pan cover during baking as indicated by point B in Fig. 2. The oven temperature was the set temperature of the static oven. Figure 3 illustrates details of the arrangement of the thermocouple to measure the sample surface temperature indicated at point A in Fig. 2. The sheathed thermocouple was passed through the pan cover and secured and sealed to it with ceramic adhesive. The welded junction was located close to the inside surface of the pan cover, but avoiding contact with it. The dough swelled up to reach the top cover in the early stage of baking. This event is called the oven spring phenomenon and finished about 90 s from the starting time of baking. The bread surface temperature in this study is defined as that measured after the oven spring event. The sudden decrease in surface temperature seen at around 3 min is considered to have been due to contact of the thermocouple junction with the swollen dough surface caused by oven spring phenomenon. The bread surface temperature defined as that after this event is shown by the solid black line in Fig. 4. Under a set temperature of 220°C, the oven air temperature reached equilibrium after about 5 min, while the surface temperature continued to rise towards the oven air temperature during the baking period.

\[
\Delta E = ((L^* - L_{0}^*)^2 + (a^* - a_{0}^*)^2 + (b^* - b_{0}^*)^2)^{0.5}
\]

where the color value of \((L_{0}^*, a_{0}^*, b_{0}^*)\) was the initial value of \(L^* = 81.24 \pm 0.77, a^*_{0} = -2.58 \pm 0.17,\) and \(b^*_{0} = 11.06 \pm 0.71.\) Standard deviations are shown by error bars in Figs. 8, 9, 10 and 11.

Results and Discussion

Oven air temperature and bread surface temperature Figure 4 shows the typical time-course changes in the oven air and bread surface temperatures measured with thermocouples at respective thermometric positions A and B in Fig. 2. The sudden decrease in surface temperature seen at around 3 min is considered to have been due to contact of the thermocouple junction with the swollen dough surface caused by oven spring phenomenon. The bread surface temperature defined as that after this event is shown by the solid black line in Fig. 4. Under a set temperature of 220°C, the oven air temperature reached equilibrium after about 5 min, while the surface temperature continued to rise towards the oven air temperature during the baking period.

Characteristic coloring curve Approximate equations were obtained to show the mutual relationships between \(a^*, b^*\) and \(L^*\) by applying

\[
\begin{align*}
L &= \frac{1}{C_1} \left( 116a + \frac{1}{C_0} \right) \\
C_3 &= \left( \frac{\frac{1}{C_0} - 1}{C_0} \right) L \\
\end{align*}
\]

Fig. 1. Sponge-and-Dough Procedure for Pullman-Type Bread.

Fig. 2. Setting the Thermocouples and Measuring Locations for Temperature and Color on the Surface of the Samples.

\(\bullet\) thermometric positions; \(\circ\), color measurement locations.

Fig. 3. Thermocouple Arrangement on the Sample Surface.
Characteristic Coloring Curve during Bread Baking

simple linear regression, multiple regression and principal component analyses. A characteristic coloring curve was then derived by solving those equations.

Figure 5 shows $a^*$ and $b^*$ against $L^*$ measured under various oven air temperatures ranging from 140 to 260°C. The average color values were calculated from then four color measuring locations just around the central thermometric position during baking. Although the plots of $a^*$ vs. $L^*$ and $b^*$ vs. $L^*$ consisted of the color values obtained at various oven air temperatures, they all appear to lie along a single curved line. The color values were found to be expressed by the following parabolic approximations:

\[
a^* = -1.63 \times 10^{-2} \times (L^* - 44.08)^2 + 11.72 \quad (1)
\]

\[
b^* = -1.55 \times 10^{-2} \times (L^* - 56.48)^2 + 21.58 \quad (2)
\]

where the regression coefficients are $R^2 = 0.95$ in Eq. 1 and $R^2 = 0.97$ in Eq. 2.

On the other hand, the results of the multiple regression analysis with $a^*$ and $b^*$ as explanatory variables and $L^*$ as the objective variable can be expressed by the following equation:

\[
L^* = -2.39 \times a^* + 2.50 \times b^* + 23.70 \quad (3)
\]

where the regression coefficient is $R^2 = 0.93$. 

---

Fig. 4. Typical Time-Course Changes in the Temperatures of the Oven Air and Bread Surface.
The bread surface temperature was measured at position A, and the oven air temperature was measured at position B in Fig. 2.

Fig. 5. Regression Curves of $L^*$ against $a^*$ and $b^*$ for White Bread Samples at Various Oven Air Temperatures.
Each point is presented as the mean with SD of the color values for four locations around position A in Fig. 2. △, 140°C; ○, 180°C; □, 220°C; ○, 260°C.
Equation 3 can also be expressed as a flat surface (Fig. 6). A principal component analysis was subsequently applied to the curved surface including data plots shown in Fig. 6 to determine the mathematical equation for the curved surface as follows:

\[
L^* = 0.90 \times 10^{-2} a^* L^* + 7.63 \times 10^{-1} b^* L^* \\
- 1.10 \times 10^{-4} L^* + 1.46 \times 10^{-3} b^2 \\
+ 3.44 \times 10^{-3} a^* b^* - 1.72b^* - 2.03 \times 10^{-5} a^2 \\
+ 38.95a^* + 1.77 \times 10^3 = 0
\]  

(4)

Since the characteristic coloring curve is the intersection line between the flat and curved surfaces including the plots, the equation of the characteristic coloring curve was determined by solving Eqs. 3 and 4:

\[
L^* = 55.20 - 4.51 \times 10^{-1} a^* - 3.81 \times 10^{-1} b^*
\]

\[
\pm \sqrt{(1.28 \times 10^{-3} - 39.40a^* - 40.30b^*)}
\]  

(5)

All the raw data for color values, that is 20 measuring locations for each sample (Fig. 2), are expressed in the 3-dimensional \( L^*a^*b^* \) color coordinate system by using MATLAB R2008a (The MathWorks, Novi, MI, USA) as shown in Fig. 7. The trace for the surface color is defined as the characteristic coloring curve for the specified dough composition.

Mohd Jusoh et al.\(^{(14)}\) have determined the color ranges for the inner crust region as \( L^* < 70, \ a^* > 0, \) and \( b^* > 13, \) so these criteria was adapted to determine the pre-heating period. Crust browning occurs when the temperature is greater than 110°C,\(^{(15)}\) and then is mainly due to the Maillard reaction rather than caramelization.\(^{(2)}\)

The Maillard reaction is principally responsible for the color development of bakery products at a surface temperature below 150 °C, while caramelization and carbonization occur at a product surface temperature above 150 °C.\(^{(12)}\) \( \Delta E \) has been found to be one of the indicators for identifying the over-baking condition, because \( \Delta E = 52 \) corresponded to the burnt sample.\(^{(10)}\) \( \Delta E > 50 \) is considered to represent the over-baking condition in this study. The overall baking process for the characteristic coloring curve was classified into the following four stages: i) pre-heating (surface temperature < 110°C), ii) Maillard reaction (110–150°C), iii) caramelization (150–200 °C), and iv) over-baking (surface temperature > 200 °C).

**Total color values and surface temperature**

The average color values discussed next were calculated from the four color measuring locations just around the central thermometric position during baking. The total color difference (\( \Delta E \)) values were plotted against the surface temperature (Fig. 8). Figure 8 includes \( \Delta E \) values for the samples baked at different oven air temperatures ranging from 140 to 260 °C, the values appearing to increase with increasing surface temperature of the sample.

**Color values and heating conditions**

The characteristic coloring curve in Fig. 7 clearly demonstrates that both \( a^* \) and \( b^* \) each have a specific value for a certain \( L^* \). Since the \( L^* \) values decreased irreversibly as baking proceeded \( L^* \) is considered to be a suitable indicator to control the surface color by baking conditions.

Figure 9 shows the \( L^* \) values against the baking time for the samples. Different symbols indicated different oven air temperatures, and standard deviations for the plots are shown as error bars. The \( L^* \) value tended to decrease with longer baking time. This appeared to reach a constant value at a certain level depending on the oven air temperature. The square symbol plots for an oven air temperature of 180 °C, for instance, appeared to reach a minimum \( L^* \) value at around 47, while the minimum \( L^* \) value for 220 °C of the filled circle symbols appeared to be around 20. Since the minimum \( L^* \) value is considered to be due to the differing equilibrium temperature of the surface, the \( L^* \) value appears to have an equilibrium value depending on the oven air temperature.

Figure 10 shows the \( L^* \) values plotted against the surface temperature for the samples baked at an oven air temperature of 220 °C. A linear relationship was observed between the \( L^* \) value and surface temperature with a regression coefficient of \( R^2 = 0.87 \). The \( L^* \) value appeared to have a specific value for each surface
temperature, the value decreasing with increasing surface temperature during the baking process.

Figure 11 shows the $L^*$ value plotted against the weight loss for the samples baked in an oven air temperature range of 180–260 °C. A linear relationship was apparent at each oven air temperature. The gray and black solid and dotted lines show the approximate plots for oven air temperatures of 180, 220 and 260 °C, and the approximate equation with coefficient of determination is that for 220 °C. These results suggest that the $L^*$ value could be estimated from the weight loss. The $L^*$ value decreases with increasing weight loss, the rate of decrease of $L^*$ for the samples baked at an oven air temperature of 260 °C being greater than that for the samples baked at 180 and 220 °C. The color values move along the characteristic coloring curve from the largest $L^*$ value for the initial dough to the smaller values, and these observations suggest that the color values for the samples baked under the highest oven air temperature changed to the greatest extent during the same baking period.
Conclusions

The color values for the surface of baked bread were measured for different baking times and for different oven air and bread surface temperatures. A similar trace for the surface color values was obtained from samples baked at various oven air temperatures. The trace defines the characteristic coloring curve, and the formula to predict the curve is proposed. Different formula might be needed for bread baked from different dough compositions. The curve indicates that $a^*$ and $b^*$ respectively had specific values for a certain $L^*$ value. $L^*$ appeared to have different minimum values according to the oven air temperature. A linear relationship was apparent between $L^*$ and the weight loss for each oven air temperature. The weight loss could be considered as one of the parameters for controlling and designing the overall baking process. The characteristic coloring curve for the specified dough composition for white bread samples identified the following four baking stages: i) pre-heating (surface temperature < 110 °C), ii) Maillard reaction (110–150 °C), iii) caramelization (150–200 °C), and iv) over-baking (surface temperature > 200 °C).

Acknowledgment

Special thanks are given to Dr. Ken-ichi Kudoh of School of Veterinary Medicine at Kitasato University for his technical assistance.

References