Journal of Food Engineering 128 (2014) 79–87

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Peeling mechanism of tomato under infrared heating: Peel loosening and cracking

Xuan Li[a], Zhongli Pan[a,b,*], Griffiths G. Atungulu[a,1], Delilah Wood[c], Tara McHugh[b]

[a] Department of Biological and Agricultural Engineering, University of California, Davis, Davis, CA 95616, USA
[b] Processed Food Research Unit, Western Regional Research Center, USDA Agricultural Research Service, Albany, CA 94710, USA
[c] Bioproduct Chemistry and Engineering Research Unit, Western Regional Research Center, USDA Agricultural Research Service, Albany, CA 94710, USA

ARTICLE INFO

Article history:
Received 18 July 2013
Received in revised form 15 December 2013
Accepted 22 December 2013
Available online 28 December 2013

Keywords:
Infrared radiation
Tomato peeling
Puncture test
Scanning electron microscopy
Stress analysis
Modeling

ABSTRACT

Critical behaviors of peeling tomatoes using infrared radiation heating are thermally induced peel loosening and subsequent cracking. Fundamental understanding of the two critical behaviors, peel loosening and cracking, remains unclear. This study aimed at investigating the mechanisms of peel separation for tomatoes subjected to a newly developed infrared dry-peeling process. Microstructural changes in tomato epidermal tissues under infrared heating were compared with those of fresh, hot lye and steam treated samples. Theoretical stress analyses coupled with the experimentally measured failure stress of tomato skin were combined to interpret the occurrence of peel cracking within a framework of elastic thin shell theory. With the use of light microscopy and scanning electron microscopy, it was observed that peel loosening due to infrared heating appeared to result from reorganization of extracellular cuticles, thermal expansion of cell walls, and collapse of several cellular layers, differing from samples heated by hot lye and steam. Crack behaviors of tomato skin were attributed to the rapid rate of infrared surface heating which caused the pressure build-up under the skin and strength decrease of the skin. In order to achieve a sufficient skin separation for effective peeling using infrared, promoting rapid and uniform heating on the tomato surface is essential. The findings gained from this study provide new insights for developing the sustainable infrared dry-peeling technology.

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1. Introduction

Peeling is a particularly important unit operation in the production of canned fruits and vegetables. The process can affect the palatability and nutritive values of final canned products (Li, 2012). From a processing standpoint, the currently used lye and steam peeling methods are water and energy intensive, and pose serious salinity issues and wastewater disposal problems (Barringer, 2003; Masanet et al., 2007; Pan et al., 2009; Rock et al., 2011; Li et al., 2013). To address these challenges, a sustainable alternative of peeling tomatoes using infrared radiation heat without relying on water, steam, and chemicals has been developed. This peeling method is named as infrared dry-peeling (Pan et al., 2009). The infrared dry-peeling technology has been successfully tested both at the bench scale and pilot scale using tomatoes from multiple harvesting seasons. Currently, onsite demonstrations to compare the performance of the new method with conventional lye and steam peeling methods are being conducted at various tomato processing plants in California. To further develop the technology and make it commercially applicable, clear elucidation of the mechanism underlying infrared dry-peeling of tomatoes is crucial. Although several experimental and modeling aspects have been addressed in our previous investigations (Pan et al., 2009; Li et al., 2011; Li, 2012; Wang et al., 2013), the thermally induced physical and biochemical changes of tomato peel, in particular the peel loosening and subsequent cracking phenomena, appear different from traditional wet-peeling methods and have not be fully understood. Study of the behavior of peel loosening and cracking should provide insight into the mechanism of dry-peeling of tomatoes using infrared.

Limited studies have been conducted to determine the peeling mechanisms (Floros and Chinnan, 1988). Most previous research concentrated on prediction of peeling performance or optimization of various peeling processes mainly for the widely used lye and steam peeling (Barreiro et al., 1995; Das and Barringer, 2005; Milczarek and McCarthy, 2011; Garcia and Barrett, 2006a,b; Matthews and Bryan, 1969; Schlimme et al., 1984; Toker and Bayndrl, 2003; Wongsa-Ngasri, 2004). Possible mechanisms of steam and lye peeling of pimento pepper and tomato were proposed based on examination of the skin microstructural

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[*] Corresponding author. Address: Processed Foods Research Unit, USDA-ARS-WRRC, Albany, California 94710, USA. Tel.: +1 510 559 5861; fax: +1 510 559 5851.
E-mail addresses: zhongli.pan@ars.usda.gov, zlpan@ucdavis.edu (Z. Pan).

[1] Dr. Atungulu's present affiliation is the Department of Food Science & Division of Agriculture, University of Arkansas, Fayetteville, AR 72704, USA.

0260-8774/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jfoodeng.2013.12.020

changes under different peeling conditions (Floros and Chinnan, 1988, 1990; Floros et al., 1987). In the steam peeling process, the main cause of skin separation is a combination of biochemical and physical changes due to the effects of high temperature steam. In lye peeling, chemical diffusion of hot lye solution into the tissue with subsequent dissolving of the cell wall materials is the primary cause of skin release. Light Microscopy (LM) and Scanning Electron Microscopy (SEM) have proved to be useful tools for observing the microstructural changes in skin morphology and anatomy occurring during lye and steam peeling of several vegetables, including tomatoes (Floros and Chinnan, 1990; Mohr, 1990). These microscopic techniques can be used to determine whether the loosened microstructure of infrared heated tomatoes is different from that resulting from lye and steam treatments. Both of the above mentioned peeling mechanisms may not directly apply to infrared dry-peeling because neither steam, water, nor chemicals are used. Instead, radiative thermal effects resulting in substantial changes in strength and biomechanical properties of tomato skin are presumably the main cause for infrared induced peel loosening and cracking.

Several techniques have been attempted to experimentally determine skin strength and membrane biomechanical failure, including tensile, puncture, and bursting diaphragm methods (Calvin and Oyen, 2007; Haman and Burgess, 1986; Miles et al., 1969). The puncture-based method is a widely accepted approach for obtaining skin strength and failure stress. In this test, a force is applied uniformly on the skin membrane by using a smooth round-ended probe or a uniform pressure loading so that the skin deforms in response to membrane biaxial tension. This technique enables detection of the increase in pressure on the skin membranes surrounding the fruit (Haman and Burgess, 1986; Henry and Allen, 1974). In light of former mechanical studies, the present study estimated the rupture stress of tomato skin during infrared peeling by determining the force–displacement relationship of the skin membrane. Because the tomato skin is much thinner than the overall fruit diameter, tomato skin is considered as a thin-walled shell (Considine and Brown, 1981; Henry and Allen, 1974). The stress on a thin spherical shell by an internal pressure loading under constant temperature can be estimated by using the membrane theory for spherical shells (Timoshenko et al., 1959; Upadhyaya et al., 1986, 1985). In this study, shell mechanics were applied for the analysis of the transient stress changes within the skin. The results were further analyzed to quantitatively evaluate the relationship between skin mechanical behavior and peel cracking susceptibility.

The specific objectives of this study were to (1) compare the morphologies of epidermal cells of tomatoes subjected to infrared, lye, and steam treatments and fresh tomatoes; (2) use puncture test to determine tomato skin rupture stress after infrared heating; and (3) investigate the correlations between transient skin stress and increasing temperature during infrared heating by using an integrated approach of experimental measurements and theoretical analysis.

2. Materials and methods

2.1. Experimental setup and sample preparation

Tomatoes of cultivars CXD179 and AB2 with uniform ripeness and size were subjected to infrared heating from two sides for 60 s. Tomatoes were collected at red-matured stage according to the USDA standard (i.e., USDA tomato classification 6) (Li et al., 2013). Only defect-free tomatoes at a size level ranging from 42 mm to 54 mm were used for peeling and subsequent measurements. During infrared heating, a tomato was rotated continuously at a speed of 1 rpm by means of a motor driven turntable to receive uniform heating. A custom-designed metal holder was used to place the tomato between the vertically aligned emitters (Li et al., 2013). The specific infrared heating setup and procedure are described in our previous publications (Pan et al., 2009; Li, 2012). During infrared heating, initial peel cracking was visually noted and the time was recorded by a stopwatch. Peel cracking was normally accompanied by a sudden sound due to skin rapture during infrared heating. After infrared heating, each treated tomato was sealed in a plastic bag to prevent further moisture loss, and it was allowed to cool to ambient temperature in the laboratory for about half an hour. Peels from these tomatoes were then used for microstructural studies and puncture tests that are described later.

Light microscopy (LM) imaging was used to observe the layer separation in pericarp tissue of tomato treated by 60 s infrared heating. Pericarp cubes (approximately 1 cm^3) of tomato with the skin attached were cut from the equatorial region of the tomato and prepared by fixation and critical point drying methods previously described (Li, 2012). Specimens were then viewed and photographed by using a Leica MZ16F stereoscope (Leica Microsystems, Wetzlar, Germany). Digital images were obtained with a QImaging Retiga 2000R FAST color camera (QImaging, Surrey, B.C., Canada). Representative images were presented.

2.2. Low temperature high resolution scanning electron microscopy

Tomato pericarp tissue (approximately $3 \times 3 \times 4$ mm) was obtained from the middle region of the tomato immediately after infrared heating. Each tissue specimen was trimmed to a wedge shape and mounted onto a copper sample holder with Tissue-Tek adhesive (Sakura Finetek USA Inc., Torrance, Cal., USA) and then prepared for low temperature SEM that was conducted with an Alto 2500 cryo system (Gatan Inc., Pleasanton, Cal., USA). The sample holder was attached to the rod of a vacuum transfer device and plunged into super-chilled liquid nitrogen. The specimen was evacuated, pulled up into the vacuum transfer device, and transferred to a cryo preparation chamber. The specimen was fractured in the cryo preparation chamber at approximately −180 °C, warmed to −85 °C and held at that temperature for 15 min to remove excess surface water. The specimen was then cooled by shutting off the heater of the cryo system to less than −135 °C, sputter coated with gold palladium, and transferred to the cryo stage specimen chamber in the SEM. All samples were observed and photographed below −135 °C at 2.0 kV by means of a Hitachi S-4700 field emission SEM (Hitachi High-Technologies Corp., Tokyo, Japan). Digital images were collected at 2180×960 pixels and were viewed under the scanning electron microscope at 400× magnification for the outer surface of tomato skin and at 200× and 400× magnification for the cross-sectional images of tomato dermal system. Fresh tomatoes prepared by the same method were used as a control.

To better understand infrared thermal effects on changing the tomato microstructure, a set of experiments was conducted to compare the differences of tomato samples treated with infrared, lye and steam heating for the same time period (60 s). Lye treated samples were prepared by using sodium hydroxide as described in Pan et al. (2009). Steam treated tomatoes were obtained by using saturated steam from boiling water under atmospheric pressure as described in Li (2012). A minimum of three replicates were obtained for each treatment method.

2.3. Measurement of skin rupture

A small segment of skin membrane was carefully dissected from the peeled skin by using a cork borer with a diameter of