Available online at www.sciencedirect.com
ScienceDirect
BioSystems 90 (2007) 602–613
Bio Systems
www.elsevier.com/locate/biosystems

Mathematical modeling of laser based potato cutting and peeling

A. Carlos O. Ferraz, Gauri S. Mittal, Walter K. Bilanski, Hussein A. Abdullah *

School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1

Received 18 January 2006; received in revised form 9 January 2007; accepted 23 January 2007

Abstract

A mathematical model is developed and validated to predict the depth of cut in potato tuber slabs as a function of laser power and travel speed. The model considers laser processing parameters such as input power, spot size and exposure time as well as the properties of the material being cut such as specific heat, thermal conductivity, surface reflectance, etc. The model also considers the phase change of water in potato and the ignition temperature of the solid portion. The composition of the potato tuber is assumed to be of water and solid. The model also assumes that the ablation process is accomplished through ejection of liquid water, debris and water vapour, and combustion of solid. A CO_2 laser operating in c.w. mode was chosen for the experimental work because water absorbs laser energy highly at 10.6 μm, and CO_2 laser units with relatively high output power are available. Slabs of potato tuber were chosen to be laser processed since potato contains high moisture and large amounts of relatively homogeneous tissue. The results of the preliminary calculations and experiments concluded that the model is able to predict the depth of cut in potato tuber parenchyma when subjected to a CO_2 laser beam.

Keywords: Laser cutting; Laser modeling; Potato cutting; Potato peeling; Biological material

1. Introduction

Recent advances in manufacturing applications of lasers have been due to their high precision, high productivity, flexibility and the effectiveness with which they can be incorporated into automated manufacturing environments. Laser has been held as a potentially useful manufacturing tool for a variety of applications. It produces a coherent, highly directional beam of light. The laser's properties of monochromaticity and spatial coherence allow the beam to be focused to an extremely small spot by a lens system, to produce a high power density laser beam used for welding, cutting, drilling or material processing.

The unique characteristics of the interaction of laser with material has revolutionised many techniques in material processing such as precise removal of small portion of material, precision drilling, localised thermal treatments, cutting without mechanical stresses, cutting complex contours, and welding with little heat affected zone (HAZ). Presently these techniques are available on an industrial scale, and laser systems and shops are used in many industries worldwide.

During the last 10 years surgical techniques have also benefited with the advent of the laser. Features such as tissue selectivity, non-contact process and wavelength-dependent penetration have made laser applications in the medical field innumerable. Recently, the use of lasers in food processing is getting attention, e.g., the application of lasers to cut cheese slices as researched by Li and Choi (2004).

This work presents a model and process for non-traditional cutting tool of potato tuber parenchyma

* Corresponding author. Tel.: +1 519 824 4120x53346; fax: +1 519 836 0227.
E-mail address: habdulla@uoguelph.ca (H.A. Abdullah).

0303-2647/$ – see front matter © 2007 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.biosystems.2007.01.004

Nomenclature

A	area of the exposed surface of the control volume (m^2)
C_p	specific heat of product (J (kg °C))
C_s	specific heat of solid phase (J (kg °C))
C_v	specific heat of water vapour (J (kg °C))
C_w	specific heat of liquid water (J (kg °C))
d	depth of cut (m)
d_e	experimental value for depth of cut (m)
D	beam diameter (m)
f_1	fraction of the total control volume occupied by the solid that will be combust (decimal)
f_2	fraction of the total control volume occupied by the water that will be vaporised (decimal)
f_3	fraction of the total control volume occupied by the solid that will be rejected (decimal)
f_4	fraction of the total control volume occupied by the solid that will be ejected by explosion (decimal)
F	loss factor (decimal)
H	thermal conductivity of product (J/kg)
K	thermal conductivity of the product (J/(m s °C))
L	latent heat of vaporisation for water (J/kg)
L	length of cut (m)
m_{cs}	mass of combusted solid (kg)
m_{es}	mass of solid ejected by explosion (kg)
m_{ew}	mass of water ejected by explosion (kg)
m_s	total mass of solid (kg)
m_{vw}	total mass of vaporised water (kg)
m_w	total mass of water (kg)
M	total mass removed after a given exposure time (kg)
P	laser beam power at the surface of the product (W)
Q	total heat generation through combustion (J)
R	surface reflectance at 10.6 μm
S	cross sectional area of the cut (m^2)
T_i	ignition temperature (°C)
T_m	mean temperature of the control volume (°C)
T_o	initial equilibrium temperature of target (°C)
T_p	temperature at which vapour formation starts (°C)
T_s	maximum temperature of the non-combusted solid fraction (°C)
T_v	maximum vapour temperature (°C)
Δt	exposure time to laser radiation (s)
ΔT	temperature gradient (°C)
v	travel speed (m/s)
V	control volume (m^3)
V_{cs}	volume occupied by the combusted fraction prior to combustion (m^3)
V_{es}	volume occupied by the ejected solid fraction (m^3)
V_s	total volume of the solid phase (m^3)
V_w	total volume of water (m^3)
X	moisture content wet basis (decimal)
Δx	thickness of the thermally affected area at the bottom of the control volume

Greek symbols

ρ_p	density of potato tissue (kg/m^3)
ρ_s	density of solid phase (kg/m^3)
ρ_w	density of water (kg/m^3)

slabs using CO_2 laser. This model constitutes an innovative technique that can be used in a wide range of vegetable cutting applications. The proposed process can improve the product quality and shelf life of the potato slabs. Selection, control and optimisation of the laser cutting parameters are essential to achieve a successful process. Any minor variation of these parameters will deteriorate the surface quality due to oxidation or cooking of the potato tuber. This non-contact cutting process has no tool wear and reduces the chances of contamination and hazardous associated with ordinary cutters or blades. Moreover, it reduces microbial load transfer from cutters and eliminates cutter-sharpening time and cost. Finally, the system will improve safety and productivity, and potentially reduces the compensation claims related to workplace injuries.

2. Laser pealing and cutting of potatoes

A pre-ablation process was observed during laser processing of aortic tissue in which the water phase change was characterised through the development of high vapour pressure with consequent expansion and disruption of the cell walls and interstitial spaces of the tissue (Versdaasdonk et al., 1990). The presence of explosions in laser processing was first mentioned by Langerholc