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Development of a ‘millimanipulation’ device to study the removal of soft solid fouling layers from solid substrates and its application to cooked lard deposits

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ABSTRACT

A mm-scale scraping device was developed to study the removal behaviour of soft solid fouling layers (thickness 0.5–10 mm) from solid substrates. A blade is dragged through the circular or rectangular samples at controlled speed and the resistance forces measured. Tests with a viscous liquid (honey) and viscoplastic material (a Vaseline®-carbon black paste) indicated that cohesive deformation dominated the measured force. Two model food soils were: (i) unbaked lard and (ii) lard baked for different times with and without added ovalbumin. The cohesive strength of the baked lard, and its removal behaviour, changed noticeably following autoxidative polymerisation. Ovalbumin delayed the onset of polymerisation.

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1. Introduction

The formation of fouling layers from baked fats and oils is a widespread problem in food processing, causing equipment degradation, unhygienic conditions and, on household appliances, an undesirable appearance. Food fats and oils are mixtures of mono, di- and tri-glycerides as well as other hydrophobic components. During frying and baking, proteins and starches can be added to the melt. Fouling deposits are formed by oxidative polymerisation of the unsaturated components to give solid or semi-solid layers, which can adhere strongly to the process surfaces. Extended (or repeated) heat treatment promotes further polymerisation, colour changes and ultimately, at higher temperatures, degradation to carbonaceous (coke) layers.

These layers are amongst the most challenging to remove and cleaning often requires strong chemical treatments and/or large mechanical forces. Both of these can lead to degradation of the underlying substrate and an increase in surface roughness (i.e. scratches), which can increase the propensity for further fouling and microbial growth. Cleaning baked-on fat soils often involves a combination of chemical and mechanical actions, wherein a chemical reagent promotes softening of the soil layer so that it can be removed by fluid shear, impacting liquid jets or mechanical friction. Being able to measure the forces involved, and thereby the rheology and evolution of microstructure, of these materials during cleaning is highly desirable for understanding cleaning mechanisms and developing cleaning agents. As stiff semi-solid materials, these soils do not lend themselves to study by

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Nomenclature

Roman

a	Carreau–Yasudo model parameter, –
f	measured force, N
f_I	force component to displace material ahead of the blade, N
f_{II}	force component to raise displaced material, N
f_{III}	force component to resist material underneath blade, N
F_w	force per unit width, $N m^{-1}$
$F_{w,0}$	force per unit width at $r/R=0$, $N m^{-1}$
F_w^0	plastic component of F_w , $N m^{-1}$
F_w^I	force per unit width to displace material ahead of the blade, $N m^{-1}$
F_w^{II}	force per unit width to raise displaced material, $N m^{-1}$
F_w^{III}	force per unit width to resist material under the blade, $N m^{-1}$
$\bar{F}_w$	average force per unit width, $N m^{-1}$
g	acceleration due to gravity, $m s^{-2}$
G'	elastic modulus, Pa
G''	viscous modulus, Pa
L	blade thickness, m
m	Carreau–Yasudo power-law index, –
r	distance from sample center and millimanipulation tool, m
R	sample radius, m
R_{ft}^2	coefficient of determination, –
s	scrape depth, m
t	time, s
t_0	scraping time, s
V	scrape speed, $m s^{-1}$
$V_{displace}$	sample velocity at the substrate, $m s^{-1}$
$V_{substrate}$	sample velocity at the substrate, $m s^{-1}$
w	width of the blade in contact with sample, m
w_t	width of the millimanipulation blade, m
x	distance scraped through sample relative to the point of first contact, m
y	co-ordinate, –

Greek

δ	clearance underneath millimanipulation blade, m
δ_0	initial thickness of soil, m
$\dot{\gamma}$	shear rate, s^{-1}
η	apparent viscosity, Pa s
η_0	viscosity at 0 shear rate, Pa s
η_∞	viscosity at infinite shear rate, Pa s
λ	characteristic viscoelastic time, s
τ_w	wall shear stress, Pa

Acronyms

BHT	butylated hydroxytoluene
DSC	differential scanning calorimetry
FT-IR	Fourier transform infrared spectroscopy
GPC	gel permeation chromatography
SS	stainless steel
Vas	Vaseline®
VCB	Vaseline® black paste

existing hydrodynamic devices such as the parallel plate flow cell (Bakker et al., 2003), impinging jet (Bayoudh et al., 2005), radial flow cell (Detry et al., 2007), rotating disc (Garca et al., 1997), the plynometer (Zorita et al., 2010) and fluid dynamic gauging (Chew et al., 2004). These all require the user to observe the moment and nature of removal at a length scale of several microns and above.

At smaller length scales, atomic force microscopy has been used to characterise adhesion and cohesion of foodstuffs such as caramel, sweetened condensed milk and Turkish delight (Akhtar et al., 2010) and biofilms (Garrett et al., 2008). Of the techniques mentioned, however, none provide a direct measure of the forces within a soil or the strength of attachment to the fouled surface. With the exception of the plynometer, they all generally require large liquid volumes and/or are time intensive. We present the commissioning of a device that is easy to use, requires little or no cleaning liquid and can make measurements quickly (≤ 5 min).

1.1. From micro- to milli-manipulation

Zhang and co-workers developed the micromanipulation technique at the University of Birmingham for studying the deformation of cells (Zhang et al., 1991) and their mechanical properties (Zhang et al., 1992; Yap et al., 2006). A modified ‘micromanipulation’ device was developed by Zhang and Fryer (Liu et al., 2002) to study the adhesive and cohesive forces within soiling layers. With this device, a horizontal bar ($30 \times 6 \times 1$ mm) is moved through the material at a set height from the substrate and the force on the bar measured. It is a controlled strain (or deformation) test, whereas the hydrodynamic devices mentioned above employ controlled (or estimated) shear stress conditions. By adjusting the level at which the tool is pulled through the layer, the technique can investigate cohesive (soil–soil) or adhesive (soil–substrate) interactions. Table 1 summarises studies where micromanipulation has been used to study foodstuffs, including proteinaceous (Liu et al., 2006a) and starch layers (Liu et al., 2006b). These studies have shown how sample rheology and soil–substrate interfacial properties affect both the strength of attachment and the type of removal observed.

The heterogeneity and the high cohesive strength of food fat soils prompted our development of a ‘millimanipulation’ tool designed to measure larger forces and work with deep layers, of thickness 0.2–10 mm. Baked fat layers, for example, have greater strengths than the material reported in Table 1. The strength of layers in the aforementioned studies ranges from ~ 0.3 to $80 J m^{-2}$ (as defined below). The millimanipulation device presented here, is shown to work on materials with a wider range of strength, including honey ($\sim 0.4 J m^{-2}$) and baked lard ($\sim 420 J m^{-2}$).

The schematic in Fig. 1(a) illustrates the working action: a vertical stainless steel blade is moved horizontally through the layer at velocity V . The layer is scraped from initial depth, δ_0 , to final depth, δ . The force required to impose the strain is measured and video microscopes are used to record the deformation behaviour. The force measured, f , includes components required to (see Fig. 1):

- (I) Deform material in the layer of thickness s , ahead of the blade, f_I ;
- (II) Displace the deformed material, usually upwards along the face of the blade, f_{II} ;

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