DEVELOPMENT OF A NANOTECHNOLOGY INFORMED CLEAN-IN-PLACE STRATEGY:

EFFECT OF INTERFACIAL CHARACTERISTICS ON MILK FOULING AND CLEANING MECHANISMS

by

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ABSTRACT

Proteinaceous fouling is a serious concern for food processing, as well as in other sectors such as biomedical devices and the marine industry. To mitigate surface fouling, this thesis aims to determine the role of surface parameters alongside their synergetic effects on the fouling formation process, as well as on the subsequent cleaning mechanism, under realistic conditions.

It has been demonstrated that surface roughness, temperature, changes in surface composition, as well as the temperature difference between liquid and substrate govern the interfacial interactions in fouling, and therefore will control initial and subsequent formation of surface fouling layers. Liquid wettability on 316L stainless steel (SS316) was favoured by increased surface roughness and wall temperature, showing how fine surface finishes are effective in reducing liquid adhesion.

Polishing of industrial surfaces may lead to textured surfaces that can lead to anisotropic liquid motion in a particular direction, affecting liquid spreading mechanism, especially when temperature increases for thermal treatment. On fine surface finishes, there was an isotropic wetting. However, as surface roughness increased, there was a preferential liquid spreading along the directional orientation of the polishing grooves and a reduction of the wetting area length along the cross-section orientation. Liquids with high surface tension showed a reduced anisotropic wetting, as spreading and wetting are governed by surface tension forces. For those liquids with low surface tension, there was a marked anisotropic wetting process where gravity and capillary forces, along with the effect generated by the surface periodic geometries that the liquid movement must overcome, favoured liquid spreading through surface grooves. Although temperature affected considerably liquid properties and the subsequent surface wetting, the interfacial wetting area was not significantly affected as surface temperature increased from 25

to 80°C. Therefore, in addition to requiring a fine surface finish to reduce adhesion of liquids, the polishing of surfaces should be performed along the flow direction of the industrial processing line to avoid transversal surface geometries that could interfere liquid motion in a stick–slip manner, and favour the subsequent adhesion of liquids, biomolecules or other bulk compounds that could act as a fouling source.

The surface free energy (SFE) of SS316L and its components remain constant between ambient and pasteurisation temperatures, but SFE is increased as surface roughness increases. As fouling develops, the SFE evolves, depending on the characteristics of the deposit formed. Our results confirmed that milk fouling kinetics, foulant characteristics, as well as the subsequent removal mechanism are found highly dependent on the temperatures used, liquid and surface temperatures, demonstrating that milk fouling begins with the surface adsorption of proteinaceous species from the bulk fluid.

To control surface fouling, it is critical to modulate the initial adsorption of proteins, emphasising an urgent need for developing anti-fouling materials. A global approach is to modulate surface energetic and topographic characteristics. Surface structuration leads to a super-/hydrophobic wetting state, where liquid is partly suspended by the air entrapped within surface geometries, hindering liquid penetration. We demonstrated that despite surface hydrophobicity increased upon surface structuration, a free contact situation may not be equivalent to a scenario whereby continuous liquid phase is being forced to make contact with a structured surface coating. Once a structured surface is exposed to a continuous layer of water, there could be a release of the entrapped air from surface geometries which enhanced liquid adsorption. In fact, the entrapped air release increased the interfacial surface area available for the interfacial adsorption process, modulating the subsequent adhesion of biomolecules.

Surface structuration favoured drastically the adsorption process of proteins, especially for the protein of smaller size (β-Lg) as a large amount of molecules would be required to fill surface structures. Stiff proteinaceous adlayers were found on the set of functionalised coatings, indicating stronger adhesion mechanisms due to conformational reorientations of proteins to facilitate surface binding, especially BSA. In contrast, surface structuration led to the formation of soft adlayers as the filling of surface geometries might affect protein conformation and favour protein superposition, hindering removal.

In conclusion, adlayers of proteins are immediately and ubiquitously present on all the surfaces investigated, where adsorption is highly dependent on both surface and protein physicochemical properties, as well as the temperature profile used for thermal treatment. The characteristics of the irreversibly adsorbed proteins constitute such primary layer that plays a direct role in the overall bio-/fouling phenomena, controlling the successive deposition of any other biological or non-biological material, shifting from surface-deposit to deposit-deposit interactions.