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'Semi-closed' Microfluidics Systems in the Modification of Surface Adhesion

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Abstract

When the majority of efforts to control adhesion from surfaces currently focus on a direct modification of the surface, either chemically or physically, perhaps a non-superficial approach where the action occurs underneath the surface can provide a competitive alternative. In this comment we highlight a methodology used to control adhesion from flexible surfaces. This is based on 'semi-closed' flexible microfluidics systems. Three basic functionalities are derived from this methodology. In one case the system is used to improve adhesion; in an extreme opposite case to prevent adhesion and in a somehow intermediate functionality it provides a switchable system in which the surface can be reversibly changed from adhesive to non-adhesive.

Keywords: Microfluidics systems; Fibres; Fluids; Semi-closed

Humankind has used adhesives since time immemorial. Birch bark, for example, was used as a natural adhesive in prehistorical time. Nowadays, synthetic adhesives are present nearly everywhere we look; they are used in clothing, furniture, vehicles, electronics, medicine etc. Most applications and thus development of adhesives are related to permanent chemical bonding. In the last decade switchable adhesives which can quickly alternate between strong bonding and delamination has aroused interest in both academia and industry. This has been inspired by the hierarchical and fibrillar structures observed in insects' and gecko's feet which allow a fast animal displacement on vertical and inverted substrates [1]. Long and slender fibres with mushroom-like tips can remarkably increase feet's adhesive strength to surfaces due to splitting of the contact patch into multiple smaller contact spots; this requires greater energy for the crack propagation than in the case of a larger single contact. Different artificial structures have mimicked this principle and rely on external stimuli such as magnetic and electric fields [2-6], mechanical impulses [7-10] and environmental changes such as temperature [11-13], pH [14] and solvent [15,16], to trigger adhesion or delamination from surfaces. In most cases the stimuli act directly on the surface modifying its chemical properties or geometry. Recent works have proposed non-superficial actuation where the surface deformation is triggered by events taking place far from the surface [13,17-19]. The main advantage of such non-superficial methods is that while adhesion from the surface is changed, the chemical properties remain unmodified. This can be of particular relevance for applications involving cells and tissue. A novel scheme proposes the use of 'semi-closed' microfluidic systems as a non-superficial method to modify adhesion from flexible surfaces.

The first attempt to use a microfluidic system to modify the adhesion from a surface was conducted by Majumder et al. [20] in 2007. Microfluidics systems (Figure 1A) typically refer to devices that manipulate, treat and, or, analyse minute quantities of fluids usually liquids in micro channels; these can perform a variety of procedures commonly carried-out in 'human-scale' laboratories. Unlike conventional microfluidics systems, in which fluids are introduced through inlets and pumped throughout the device to outlets, the microfluidic systems used by Majumder et al. had 'semi-closed' structures that enabled an empty or filled configuration of the system, i.e., somehow a closed system. They demonstrated that these 'semi-closed' microchannels underneath the surface of an elastomeric material were able to enhance its peeling strength against a flexible substrate (sketched in Figure 1B). With an appropriate geometry, these sub-surface channels improved the adhesion strength in a comparable extent to the effect of structuring the surface with fibres, i.e., contact splitting effect in gecko's feet. An even higher boost in the peeling strength was obtained by filling the microchannels with liquids of medium viscosity. The fluids were suggested to provide an enriched viscous dissipation so when the crack passed over the channels they acted as crack trapping places, which demanded higher energy to continue the propagation of the crack. In 2011 Arul and Ghatak [21] fabricated a similar 'semi-closed' system for improved normal (90º) adhesion sketched in Figure 1B. This consisted of a stack of microchannels embedded in an elastomeric sheet. The indentation of such surfaces with a threshold load resulted in the squashing of the channels. The 'self-adhesion' due to the contact between top and bottom inner walls of the collapsed channels provided a surplus in adhesion. The self-adhesion was improved by patterning and chemically treating the internal walls of the channels.

The aim of the systems thus far presented was to increase the strength of physical adhesion in a 'passive' model. One of the advantages of microfluidic systems is the easy manipulation of fluids by pumping them in and out of the system in an 'active' model. This feature has been recently explored by Carlson et al. [17] and Prieto-Lopez and Williams [18,19] as a potential mechanism to modify the adhesion of surfaces. They applied a pressure, up to ca. 800 mbar above ambient, to the semi-closed microfluidic systems and use the inflation of sub-surface micrometric reservoirs as a fast and reversible way to reduce the adhesion of elastomeric surfaces. These semi-closed systems consisted of circular chambers [17] or periodic arrays of channels and chambers [18,19], located immediately below the surface of silicone elastomers. The inflation of these chambers transformed the topography of the surface from flat into bumpy or ridged (Figure 1C). This reduced the total area readily available for contact resulting in the reduction of its adhesion to counterfaces. The controlled variation of the pressure

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applied to the sub-surface structures allowed the active regulation of adhesion from these surfaces in a fast and reversible manner without modifying its chemical composition. Prieto-Lopez and Williams [19] also demonstrated that introduction of a fibrillar texture on the surface of these semi-closed microfluidic systems was able to enhance their adhesion against rough surfaces due to an improved contact. This mechanism based on the well-developed fabrication techniques of microfluidics circumvents the need of a particular surface finish and specific material type (metallic, magnetic, etc.) which offers promising applicability in adhesive processes involving naturally rough engineering surfaces.

The inhibition of adhesion of undesired objects on surfaces is another topic of primal relevance in the field of adhesion. Applications such as anti-fouling, self-cleaning and anti-icing surfaces can be derived from this property. Clever solutions have been recently suggested as anti-fouling mechanisms; for example, the immobilization of lubricants in porous surfaces [22,23] or the introduction of lubricant droplets in a gel matrix [24]. In these systems the supply of lubricant is limited and so durability remains an issue. 'Semi-closed' microfluidic systems are emerging as an encouraging solution to prolong the non-adhesive functionality of such surfaces. Howell et al. [25] introduced a 'semi-closed' microchannel network in a silicon-oil-infused sheet of poly(dimethylsiloxane) (PDMS); this formed a composite system of silicone oil molecules trapped within the PDMS polymeric network. In this system the network of the crosslinked polymer functions as 'nano-outlets' providing a slow and continuous effusion of lubricant molecules from the inner structure towards the outer surface (Figure 1D). This continuous transfer of lubricant to the surface enables the replenishment of any loss in superficial lubrication significantly improving and prolonging the anti-biofouling property. Although the operation principle of this system is based on the continuous outflow of lubricant, it relies on the permeation of silicone oil through PDMS and so the timescale of the process is in the order of a day. Therefore within the short-time scale (less than 1 h) the system can be described as a 'semi-closed' microfluidic system. Nature's ubiquitous mechanism to control adhesion involves the secretion of glue-like fluids from animal tissue. Howell et al. replenishing mechanism for systems with long-time operation paves the way for mimicking nature's adhesive secretion mechanism.

'Semi-closed' microfluidic systems provide an alternative approach to manipulate the adhesion from surfaces. These non-superficial methodologies demonstrate an advantage against superficial techniques by maintaining a chemically unmodified surface before and after separation processes. These systems not only offer a way to improve or decrease adhesion in a permanent manner but also a quick switching mechanism between adhesive and non-adhesive surfaces. With the continuous development in fabrication techniques, microfluidics technology promises to become a powerful contribution for surface engineering.

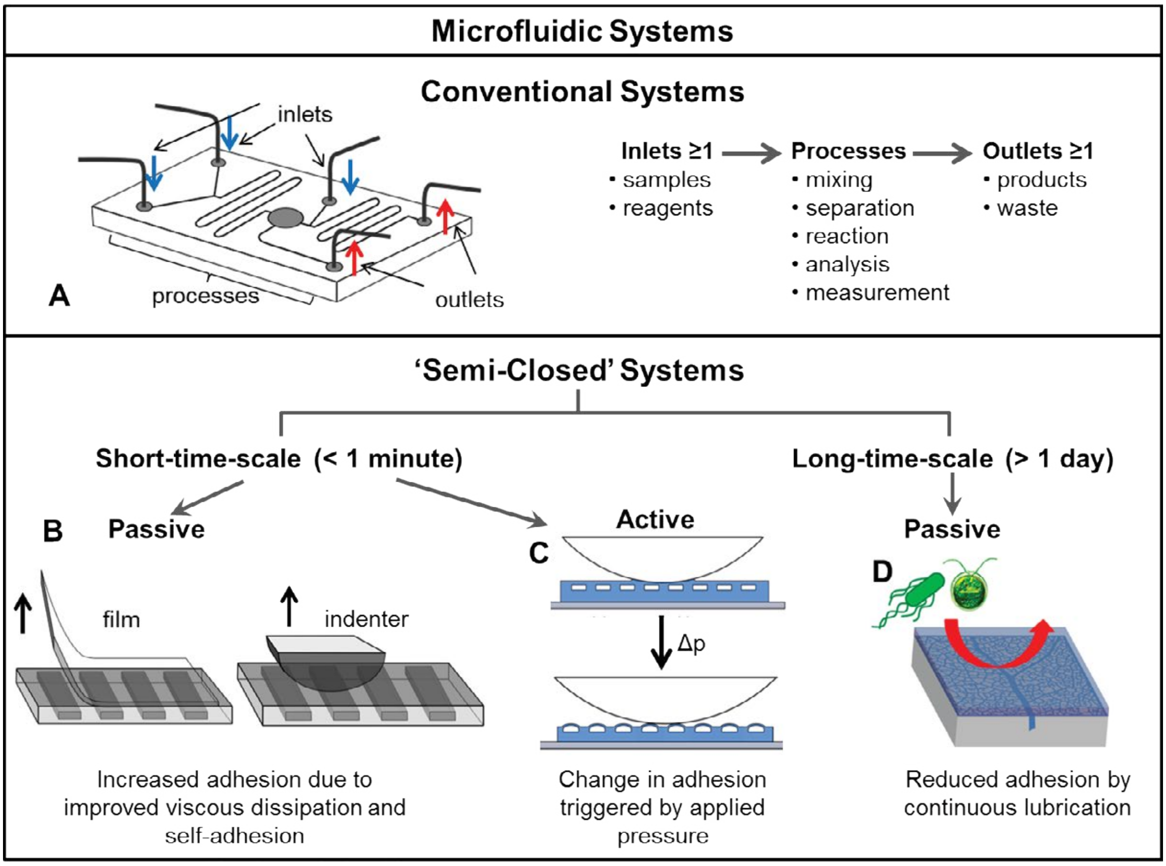

Figure 1: 'Semi-closed' microfluidics systems. **A** Traditional microfluidics devices. **B** Passive systems for short-time operation: enhanced peeling strength of elastomeric film by internal channels; simplistic representation of the works in references [20-21]. **C** Active system for short-time operation: elastomeric surface of switchable adhesion adapted from Ref. [18]. **D** Passive system for long-time operation: self-replenished anti-fouling surface with embedded reservoirs; reprinted with permission of reference [24], copyright 2015 American Chemical Society.

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