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High precision self-alignment using liquid surface tension for additively manufactured micro components

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ABSTRACT

Self-assembly of components using liquid surface tension is an attractive alternative to traditional robotic pick-and-place as it offers high assembly accuracy for coarse initial part placement. One of the key requirements of this method is the containment of the liquid within a designated binding site. This paper looks to expand the applications of self-assembly and investigates the use of topographical structures applied to 3D printed micro components for self-assembly using liquid surface tension. An analysis of the effect of edge geometry on liquid contact angle was conducted. A range of binding sites were produced with varying edge geometries, 45–135°, and for a variety of site shapes and sizes, 0.4–1 mm in diameter, and 0.5 mm × 0.5 mm–1 mm × 1 mm square. Liquid water droplets were applied to the structures and contact angles measured. Significant increases in contact angle were observed, up to 158°, compared to 70° for droplets on planar surfaces, demonstrating the ability of these binding sites to successfully pin the triple contact line at the boundary. Three challenging self-assembly cases were examined: (1) linear initial component misplacement >0.5 mm, (2) angular misplacement of components, and (3) misplacement of droplet. Across all three assembly cases the lowest misalignments in final component position, as well as highest repeatability, were observed for structures with actual edge geometries <90° (excluding 45° nominal), where the mean magnitude of misalignment was found to be 31 μm with 14 μm standard deviation.

1. Introduction

Industrially manufactured products are typically assemblies made up of many separate and often dissimilar components. The assembly techniques required to realise these finished items are therefore of key importance to product generation. The micro component industry is rapidly growing and the continual trend of component miniaturisation has led to its own set of challenges that are not present in the macro domain. Simple pick-and-place operations become complex issues due to scaling effects, as parts become smaller gravity is no longer the dominant force. This is because surface forces scale with length, whereas gravity scales with length cubed [1]. This results in release problems due to adhesion forces between components and micro handling tools. Surface-related forces such as van der Waals, electrostatic and surface tension dominate over gravitational force, which have led to novel handling strategies becoming the focus of much work. This includes the development of micro grippers [2–4], vacuum grippers [5], freeze grippers [6], as well as those based on electrostatic forces [7,8].

An additional challenge for micro assembly in an industrial environment is that the process must be both fast and precise. Current methods make use of robotics to manipulate and place components; however these solutions either build assemblies with sub-micron accuracy at low speeds, or at high assembly speeds but with low accuracy [9]. There is also a cost trade-off to be made with faster more accurate systems being significantly more expensive. To lessen the challenge of micro assembly an interesting concept is that of component self-assembly. Liquid self-assembly of components is an attractive alternative to traditional robotic pick-and-place techniques as it can offer very high final positional accuracy with fairly coarse initial placement. This means lower cost, faster pick-and-place systems, or the replacement of robotic pick and place with manual pick-and-place; leading to the advantages of either increased system flexibility, or reduced cost and higher throughput. The underlying concept behind liquid self-assembly is that features produced on the components can control droplet

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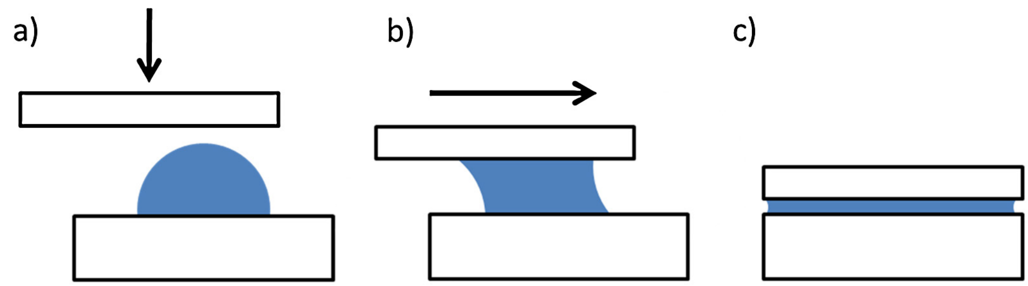

Fig. 1. Self-alignment of component using liquid surface tension. (a) Liquid droplet dispensed onto binding site and component moved into place, (b) component comes into contact with liquid droplet and meniscus is formed, and (c) restoring forces act on component and it aligns to shape of binding site due to energy minimisation.

shape, and therefore surface tension, in such a way that the lowest energy state for the liquid is achieved when the components are well aligned. This principle is illustrated in Fig. 1 which shows the droplet in place prior to assembly (a); followed by the drop wetting to both the static surface and the part (b). At this stage the non-symmetrical nature of the liquid surface results in surface tension forces that tend to move the part to a state of lowest surface energy; once the lowest surface energy state has been reached all surface tension forces are balanced (c).

The controlled spreading of the assembly liquid is a key factor in this process, and much work has been carried out into this area. Several approaches have been developed in order to alter the wetting properties of specific regions of a surface. These include (super)hydrophilic and (super)hydrophobic target sites [10–15], (super)oleophilic and (super)oleophobic for oil-based liquids [16–18], micropillar arrays to create hydrophobic regions [19,20], as well as most recently, receptor sites with sharp edges to inhibit liquid spreading [21–24]. These methods can be divided into two distinct areas; those which rely on altering the surface properties of specific regions to influence wetting behaviour, and those that utilise physical geometric structures to constrain liquid spreading. Until now the majority of the literature in this field focuses on applications involving the use of microchips assembled on silicon wafers [25–28], with modifications to surface properties being introduced through a post-build process of coating, masking and etching. Typically this is achieved by thermally growing a silicon oxide layer on the wafer before a standard photolithography and reactive-ion etching (RIE) process is carried out to pattern the oxide layer [14,21,29] resulting in a hydrophilic surface. Other techniques [26,27] also used black silicon coated with a fluoropolymer to realise a hydrophobic background material surrounding the binding sites.

As previously mentioned, one of the requirements of the self-assembly process is the confinement of the assembly liquid to a specified binding site. The ability to control liquid spreading through the use of sharp edges pinning the triple contact line (TCL) has been known for some time. The TCL is the equilibrium boundary where the solid–liquid–gas phases meet, with the shape of the liquid–gas interface determined by Young's equation:

$$0 = \gamma_{SG} - \gamma_{LS} - \gamma_{LG} \cos\theta_c \quad (1)$$

where γ_{SG} is the solid–gas interfacial energy, γ_{LS} is the liquid–solid interfacial energy, γ_{LG} the liquid–gas interfacial energy, and the equilibrium contact angle θ_c from the surface, as illustrated in Fig. 2.

Structures that control liquid spreading through halting the movement of the TCL at a defined edge are based on the mathematical inequality presented by Gibbs [30]:

$$\theta_c < \theta < (180^\circ - \alpha) + \theta_c \quad (2)$$

where θ is the contact angle of the droplet, θ_c is the Young's contact angle, and α is the angle of the sharp edge, see Fig. 3.

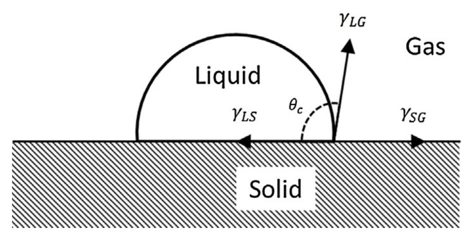

Fig. 2. Diagram illustrating the quantities used in Young's equation (1).

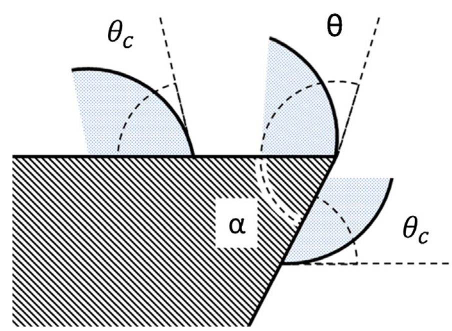

Fig. 3. Spreading of a liquid droplet meeting a sharp edge as described by the Gibbs inequality, Eq. (2).

Overflow of the liquid assembly medium beyond the defined edge of the structure is catastrophic to self-assembly processes. Once the liquid is able to travel beyond the defined edge, the part to be assembled will be drawn along with the liquid, and out of alignment. It is therefore of critical importance to maximise the contact angle of the liquid when it is pinned at the boundary if robust self-assembly procedures are to be realised.

To extend the possible application of self-assembly to new areas this work will consider the relevance of the technique to additive manufacturing (AM) processes. The additive manufacturing industry offers many exciting possibilities for the rapid, flexible and cost-effective production of next generation products across a wide range of industrial sectors. The technology is typically used for modelling, prototyping, short-run production, and bespoke items, however as the process improves its use for final component manufacture is being seen. Examples of this can be seen in medical and dental implants, as well as technical applications such as the aerospace industry [31,32]. Compared to traditional subtractive manufacturing methods AM offers much greater design flexibility with the realisation of intricate structures that cannot be manufactured using other methods, such as complex internal channels.

To our knowledge no work has been carried out to date on this manufacturing method for use in self-assembly applications using liquid surface tension. This work considers components in the 0.4–2 mm range, larger than typical micro assembly parts, as