Research Letter

Aerodynamically Assisted Jet Fabrication and Deposition of Composite Scaffolds via Concentric Needles

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Received 9 July 2007; Accepted 27 September 2007

Recommended by Tsutomu Ohzuku

Recent interests in process methodologies possessing the ability for forming scaffolds have gained a great deal of scientific attention. Essentially this has resulted from the realization that these constructs have much utility in the life sciences. In this letter, we elucidate a novel and versatile scaffold process fabrication methodology with a concentric jetting process that shows tremendous possibilities for forming stable composite scaffolds. Our studies combine a specially formulated medical grade PDMS (polydimethylsiloxane) medium together with this concentric jetting process demonstrating significant possibilities for controlled composite scaffold formation and deposition. Hence the results presented elucidate promising opportunities for using these scaffolds in the biomedical areas of research.

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1. INTRODUCTION

Processing methodologies have recently been identified as a standalone area of research as it plays a fundamental role in bridging engineering sciences with the biological world. Scaffold preparation has been of great interests to a wide research community spanning the physical and life sciences. There are several jet approaches for forming scaffolds, namely, electrospinning [1], fused deposition modelling [2], to recently unearthed electrospraying [3].

Electrospinning and electrosprays are related jet processes, sharing a common process drive, namely, an electric field. However, they are fundamentally different in terms of the associated physics as the former initiates a jet from a liquid cusp which subsequently generates continuous threads while the latter forms droplets. In both cases, these threads and droplets could range from the micrometer to the nanometer. Control over the alignment of these threads formed by means of electrospinning have also been successfully achieved [4]. Although electrosprays have been known to form individual droplets, recently this process was uncovered for forming continuous threads by the assembly of droplets to one another by exploiting the charge on each droplet in combination with the external electric field

[3, 5]. Currently, this process is undergoing much investigation to understand if it possesses the potential to compete with electrospinning, and if so this would enable the manipulation of these fabricated architectures both in terms of precision deposition and structural integrity. As of to date, it has been elucidated that this electrohydrodynamic jet assembly of structures has the ability to form complex components such as unsupported links between structures to overhangs [6, 7] without the aid of a mould.

Fused deposition modelling is an extrusion process where a thermoplastic or composite material is forced through a controlled diameter together with precision movement in the three axes forming a scaffold much like a cross-stacked arrangement of logs [8]. This process is essentially in the micrometer regime and has been known to form some interesting structures [9, 10]. These scaffold process fabrication approaches have already been used by scientists in the life sciences for a variety of bioapplications [11–13].

In the current work, we show here an aerodynamically assisted jetting process [14] having a concentric needle arrangement driven by a pressure difference over an orifice coupled with a specially formulated medical grade PDMS medium which has the ability to form stable composite scaffolds. Furthermore, our investigations reveal the ability to pattern

FIGURE 1: Schematic representation of the aerodynamically assisted jetting device having the concentric needle configuration for generating composite droplets and threads.

pre-organized architectures using this composite scaffold preparation methodology which is both economical and multipurpose.

2. EXPERIMENTAL

The silicone fluid designated as Med10-6607, which is a hydroxy functional dimethyl silicone polymer uses an oxime curing mechanism dispersed in a naphtha petroleum spirit assisting in maintaining its structural integrity on deposition (supplied by Polymer Systems Technology Ltd, High Wycombe, UK).

The aerodynamically assisted jetting device consists of a concentric needle arrangement encapsulated in a pressure chamber having an exit orifice placed ~ 1.6 mm below the needles (Figure 1). The pressure chamber has a second input which holds the flow of the regulated pressure from a constant supply of ~ 6 bars. Both needles were connected to two separate syringes via silicone tubing to two individual syringe pumps (Model type PHD 4400, HARVARD Apparatus Ltd., Edenbridge, UK) capable of supplying consistently low flow rates. The inner needle held the water while the outer needle accommodated the specially formulated medical grade PDMS medium (Figure 1). The viscosity, surface tension, and the density of the medical grade PDMS medium were measured and found to be approximately 5500 mPa s, 21 mNm^{-1} , and 970 kgm^{-3} , respectively. As our intention was to identify both, the ability to jet (in stable conditions) the medium and in doing so, demark the operational conditions required for forming the finest residues, we investigated a wide operational parametric space. Jetted components were

collected onto several glass microslides which were optically micrographed on deposition at several different time points. The structural integrity of the deposited residues were found to be stable over several days upon which these deposits could be peeled off the substrates.

3. RESULTS AND DISCUSSION

On traversing a wide operational parametric window of applied pressure to flow rate, we found that it was best to have the applied pressure to < 1 bar for a corresponding flow rate in the $\sim 10^{-9} \text{ m}^3 \text{ s}^{-1}$ regimes. It was found that if the flow rate was too small, this would initiate what we refer to as back flow, where bubbles would flow through the tubing to the syringe holding the media, which completely disrupted the jetting process. Conversely, if the flow rate was too high, we observed the PDMS medium to accumulate at the needle exit resulting in jet disruption to forming large residues to unstable jets. Therefore, a balance was needed for promoting the stable formation of threads. The flow rate to applied pressure combination was therefore found by initially setting up the smallest flow rates in either needle, subsequently increasing it accordingly for a constant applied pressure with the continuous analysis of the collected residues.

Continuous and stable jetting of threads was seen to take place at an applied pressure of ~ 0.07 bar for flow rates of $\sim 10^{-9} \text{ m}^3 \text{ s}^{-1}$. During this time collection of threads took place, the collected residues were seen to create a scaffold (Figure 2(a)). On examining these scaffold residues closely at high magnification, it was seen that the inner medium, water, was encapsulated in the fabricated scaffold (Figure 2(b)).

(a)

(b)

FIGURE 2: Representative optical micrographs of the collected a) composite stable scaffold and b) high magnification image of the composite threads.

The successful encapsulation of the inner medium (water) gave rise to a bubble-like structure capsulated by the fast curing PDMS medium. Such structures could be most useful in a wide range of medical-related applications where living organisms to drugs could be encapsulated within a polymer having a known degradation time allowing rapid wound healing to targeted and controlled dosage-type delivery of drugs to the human anatomy. On moving several microslides across the jet, it was found that these residues could be deposited according to a preorganized pattern (Figure 3). On either increasing the applied pressure or flow rate, respectively, the jetting process was seen to undergo unstable jetting which initiated the formation of near-annular shaped scaffold residues having randomly placed water encapsulations. At stable threading operational conditions, we observed that large areas could be patterned with ease to have a composite scaffold-like surface morphology which the authors are vigorously pursuing for investigating studies related to cell proliferation (Figure 4).

The deposits were observed over two days and found to be stable maintaining their initial structural integrity. On the third day, the scaffolds were peeled off the microslides and soaked in water for a few minutes. These structures were

FIGURE 3: Characteristic optical micrograph showing a patterned track with composite stable microthreads.

FIGURE 4: Typical micrograph illustrating patterning large areas with composite microthreads.

manually handled and found to mimic a flexible composite film.

4. CONCLUSIONS

Our investigations have elucidated that aerodynamically assisted jets formed by means of concentric needles could be used in conjunction with a PDMS polymer for the fabrication of controlled composite stable scaffolds. These scaffolds could be exploited as cell friendly surface matrices where these structures will assist cells to proliferate. The ability to control the deposition of such scaffolds give greater opportunities for cellular studies where these structures could be used for manipulating the direction of cellular growth—which could globally impact on areas such as regenerative medicine to tissue engineering active biological structures. The authors are currently constructing a three-axis computer controlled device which will hold the jetting device relative to a substrate which will then be given coordinates to follow resulting in the fabrication of a scaffold architecture in either two- or three-dimensions to a prearranged pattern.

ACKNOWLEDGMENTS

The second author thanks both Mr. Terry Dyer and Mr. Richard Winn of the Department of Mechanical Engineering for all their assistance in the construction of the coaxial aerodynamic jetting device used in this study. He gratefully acknowledges the Engineering and Physical Research Council of the UK for financially supporting both this research and a research assistantship position for the first author via Grant no. EP/D506964/1.

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