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Generation of porous solids with well-controlled morphologies by combining foaming and flow chemistry on a Lab-on-a-Chip

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ABSTRACT

We review here how millifluidic techniques can be used to construct versatile Labs-on-a-Chip, in which on-chip bubble generation and flow chemistry are efficiently combined to generate porous solids with highly monodisperse and ordered pore structures. With this approach, a liquid foam with well-controlled structural and chemical properties is first generated, which is then solidified in situ. We discuss here the interplay of various important processing parameters. In particular, we demonstrate that solidification time and foam life time need to be matched wisely in order to control precisely the properties of the final porous material. We also discuss a simple and inexpensive route to the manufacture of chemically and pressure-resistant, millifluidic Labs-on-a-Chip via the machining and hot-pressing of Cyclic Olefin Copolymers. We illustrate our review using the example of the generation of two types of hydrogel foams (synthetic acrylamide-based and biopolymer chitosan-based) and of particle foams, which may be used as green bodies for the manufacture of porous ceramics. The newly designed materials can be used to investigate fundamental questions of the structure–property relationship of porous solid.

1. Introduction

Introducing air into solid materials creates foams or sponges with a porous architecture which adds a novel and complex dimension to the properties of the material. Among these are excellent mechanical, thermal, or acoustic properties, which are extensively exploited in industrial applications and at the heart of intriguing scientific questions [1,2]. In order to control these properties, one needs to control the porous architecture of the material. With this in mind, the last decades have seen the development of a variety of foaming techniques. However, most of these techniques combine simultaneous foaming and solidification of an initially liquid mixture in a complex manner which poses a great challenge to fine-tuning and scientific understanding.

In parallel, the understanding of *liquid foams* has developed significantly over the last 20 years [3–5], providing an increasingly robust description of their physico-chemical and structural properties. Scientists now avail of a wide range of surface active agents (low molecular weight and polymeric amphiphiles, proteins, polymers, particles, etc.) to create stable foams from various liquids (including non-polar ones). Especially particle-stabilised foams can be "superstable", i.e. without change in foam structure over up to several months [6,7]. Furthermore, scientists have elaborated a large number of foaming techniques which provide excellent control over bubble sizes and bubble size distributions. Bubble sizes can be tuned from tens of micrometers to several millimeters (and even meters), and bubble size distributions can range from polydisperse to extremely monodisperse [8]. Last but not least, it is now very well understood how bubbles pack together in liquid foams, i.e. how liquid content, bubble size distribution and foam structure are related [5,9–12].

In order to build on this expertise on *liquid foams*, it is desirable to develop techniques in which solid foams are generated essentially in a two-step process [5] (Fig. 1): a sufficiently stable *liquid foam with well-controlled structural properties* is generated in a first step, and then solidified in a second one. These two steps can either be completely separated by choosing a solidification mechanism which is initiated externally at a desired moment (UV, temperature, etc.). Or, foaming and onset of solidification may occur simultaneously, but foam generation and solidification times need to be matched in order to make sure that the desired foam can be created in a liquid state, i.e. before the solidification freezes the movement of liquid and bubbles. With such a two-step approach,

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