Microfluidic Platform for Combinatorial Measurements of Polymer Properties†

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INTRODUCTION

Microfluidics is a rapidly developing technology that has found numerous promising applications in the biological and analytical communities. Rapid separations and chemical analysis of aqueous based systems can be carried out using only nanoliters of material.[1-3] At the NIST Combinatorial Methods Center (NCMC), we are interested in adapting microfluidic technology for performing combinatorial measurements on polymer systems. We have recently developed a rapid prototyping technology that makes use of a commercially available thiolene based optical adhesive to fabricate microfluidic devices resistant to many common organic solvents and monomers.[4,5]

Organic-stable microfluidic devices can be used for combinatorial measurements of polymerization reactions on chip. Formulation, processing, and measurement are combined on one device for the generation of combinatorial polymer libraries (Figure 1). This report describes the preparation of a monomer/crosslinker composition gradient, photopolymerization to form polymer particles, and collection of polymer particles into composition arrays. On-chip Raman spectroscopy coupled with digital image analysis allows for quantification of composition, monomer conversion, and polymer shrinkage.

EXPERIMENTAL[6]

Materials. Benzyl methacrylate, hexanediol dimethacrylate, dodecanediol dimethacrylate (Esstech), Irgacure 819 (Ciba) photoinitator were used as received. A Novacure 2100 UV source was used to initiate polymerization and a Raman Systems R2001 spectrometer was used for Raman measurements. Devices were fabricated from Norland NOA 81 optical adhesive as described previously[5] using (1.1 × 70 × 50) mm pieces of borofloat pyrex (Cincinantti Gasket).

On-Chip Experiments. A gradient of droplets of benzyl methacrylate and either hexanediol dimethacrylate or dodecanediol dimethacrylate crosslinker (each containing photoinitiator) was formed by joining together the monomer and crosslinker inputs into one organic stream before the site of droplet formation. The droplets were then formed at a flow focusing junction[7] with the organic phase meeting an aqueous phase of 9 mmol/L sodium dodecylsulfate solution. The devices were transferred to a computer controlled x-y motorized stage (Newport) that was used to move the array of droplets beneath a UV spot source or a Raman probe. Raman spectra were collected before polymerization and 24 h after polymerization. For the shrinkage studies, the microfluidic devices were mounted under a microscope and micrographs at 2.5 × magnification were captured with a CCD camera (JAI CV-S3200) mounted onto the microscope. Image analysis was performed using Vision Assistant (National Instruments, version 7.0) image analysis software. Droplet radii were determined for images taken both before and 24 h after polymerization, from which change in volume was calculated.

DISCUSSION

The first stage of combinatorial library preparation is the formation of organic phase monomer droplets. Methacrylate monomer solutions were introduced into a stream of water and sodium dodecyl sulfate (SDS) surfactant where monomer droplets were formed. Typical droplet sizes range from 250 μm to 600 μm in diameter and droplet sizes can be controlled by varying the relative flow rates of the organic phase and aqueous phase on the device.[5] A composition gradient was formed by varying the relative flow rates of the monomer and crosslinker input streams while keeping the overall volume of the droplets constant. These droplets are encapsulated by surfactant and do not wet the walls of the device, thus they can be manipulated on the device by the aqueous continuous phase. The use of droplets in the formation of composition gradients has the advantages isolating individual composition samples, as well as facile mixing of multiple component mixtures within individual droplets.[8]

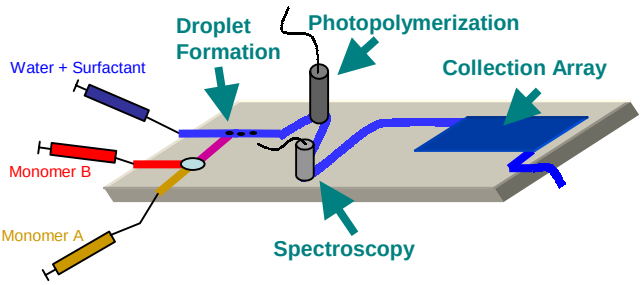

Figure 1. Schematic of a microfluidic platform incorporating elements for formation of polymer particles, spectroscopic measurements and collection of a combinatorial library of particles.

The gradient of monomer/crosslinker droplets was collected into an array of long switch back channels on the device. Such an array is shown in Figure 2, wherein colored dyes have been introduced for better visualization. Photopolymerization of monomer droplets was initiated with a UV source mounted with a fiber optic probe allowing for precise positioning of the light source over the device. For these experiments, the droplets were polymerized on the chip by passing the array of droplets under the UV probe. However, it is also possible to initiate polymerization in-line by allowing the droplets to flow through a channel beneath the light source.

Raman spectroscopy was used to monitor the polymerization reactions. The Raman spectrometer is fitted with a fiberoptic probe that allows for positioning of the probe directly above the fluidic channels. A spot size of approximately 300 μm allows for collecting spectra from individual reactant droplets or polymer particles, as well as averaging over ensembles of particles. As with the UV probe, measurements were taken by scanning over an array of droplets. Raman data was collected on the monomer / crosslinker gradient array prior to polymerization to quantify composition information and as a baseline for conversion studies. Spectra taken 24 h after polymerization were used for determining extent of monomer conversion by measuring the decrease in the C=C peak.

Figure 2. A collection of monomer droplets (approximately 300 μm in diameter) inside of a microfluidic channel. A gradient of composition is shown with benzyl methacryalte (dyed blue) and hexanediol dimethacrylate (dyed red).

For shrinkage measurements, the devices were placed under a microscope fitted with a digital camera. Digital micrographs were taken before and 24 h after polymerization. Image analysis allowed determination of the volume of individual droplets and shrinkage data

was determined from comparison of volumes before and after polymerization.

CONCLUSIONS

We demonstrate the use of organic stable microfluidic devices as a combinatorial measurement platform. Libraries of polymer formulations can be built on chip from individual monomers and crosslinkers that are polymerized directly within the device. High-throughput measurements can be performed on the entire array of compositions. Raman spectroscopy allows validation of library composition as well as measuring the progress of polymerization reactions. Optical image analysis allows for determination of polymer shrinkage. These data represent a first demonstration of the concept of correlating formulation, processing and measurement function on a microfluidic chip as a platform for combinatorial and high throughput experiments.

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