

Generation of Microcellular Biodegradable Polycaprolactone Foams in Supercritical Carbon Dioxide

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ABSTRACT: Microcellular foaming of low- T_g biodegradable and biocompatible polycaprolactone (PCL) in supercritical CO₂ has been studied. The purpose is to apply microcellular materials to drug containers and medical materials for artificial skin or bone. Effects of a series of variable factors on the foam structures, such as saturation temperature, saturation pressure, saturation time, and depressurization time were studied. The experimental results indicate that, while keeping other variables unchanged, higher satu-

ration temperature leads to reduced bulk densities and different saturation pressures result in different nucleation processes. In addition, saturation time has a profound effect on the structure of the product. © 2004 Wiley Periodicals, Inc. *J Appl Polym Sci* 94: 593–597, 2004

Key words: supercritical CO₂; foams; biopolymers; biodegradable; polycaprolactone; microcellular

INTRODUCTION

Present microcellular polymeric materials are found to have more and more applications in the biomedical field, such as guided tissue regeneration and cell transplantation. As far as guided tissue regeneration is concerned, porous implants are used as size selective membranes to promote the growth of tissue in a healing site. Ideally, the implant should be inherently biocompatible, have well-defined cell size, and be resorbable with appropriate biodegradation rates.¹ Poly(ϵ -caprolactone) (PCL) is material that meets the above demands well. PCL is a biocompatible and biodegradable aliphatic polyester that is bioresorbable and nontoxic for living organisms. Because of its unique combination of biocompatibility, permeability, and biodegradability, PCL, and some of its copolymers with lactides and glycolide, have been widely applied in medicine as artificial skin, artificial bone, and containers for sustained drug release.^{2–5}

A new method to generate microcellular poly(methyl methacrylate) foams has been reported by Goel and Beckman:^{6,7} first, samples are saturated with supercritical (SC) CO₂, and then the system is rapidly depressurized to atmospheric pressure at a constant temperature. Unlike traditional methods, it reduces glass transition temperature (T_g) of the mixture to below the experimental temperature rather than di-

rectly heating the system to a temperature above T_g . In this nucleation process, no phase separation occurs and no phase boundary meets, so the cellular structure of the foam can be retained much better.

It is well known that supercritical fluids have some unique properties such as liquid-like dissolving power and similar transportation property with a gas. CO₂, a nontoxic fluid with a relatively low critical point ($T_c = 31^\circ\text{C}$, $P_c = 7.376\text{ MPa}$) is most widely used in the supercritical fluid field. Goel and Beckman^{6–8} and Aroa et al.^{9,10} have done much valuable work on plastic materials such as polystyrene, polypropylene, poly(ethylene terephthalate), polycarbonate, PMMA,^{6–10} and biocompatible materials such as poly(lactide-co-glycolide) (PLA-PGA) and polystyrene/LCP blends^{1,11} to make them form microcellular structures in SC CO₂. In this work, we successfully generated PCL foams by using supercritical CO₂. Because of the low glass transition temperature ($T_g = -60^\circ\text{C}$) of PCL, far below the ice point, the experimental temperature in our study is much higher than T_g , which is the distinct difference from studies by other researchers.

Experimental

Materials

PCL was provided by CSIRO, CMIT of Australia in the form of ivory-white granules and used as received ($M_n = 85,000$, $T_g = -60^\circ\text{C}$, $T_m = 60^\circ\text{C}$). CO₂ with purity of 99.9% was obtained from Zhengzhou Sanfa Gas Co.

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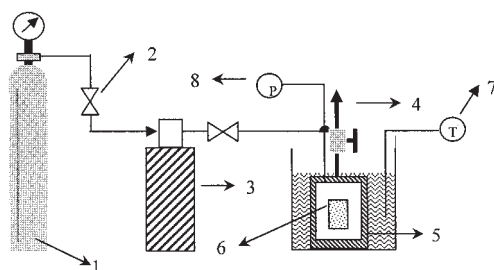


Figure 1 Apparatus description diagram: 1, gas cylinder; 2, valve; 3, syringe pump; 4, vent; 5, variable-volume reaction with view windows; 6, sample; 7, temperature circulator; 8, pressure gauge.

Apparatus

Reactions were run in a 50.0-mL high-pressure variable-volume stainless steel reactor with two glass view windows. A high-pressure syringe pump (Beijing Satellite Manufacturing Factory, DB-80) was used to charge CO_2 into the reaction vessel and attached to the reactor via a coupling and high-pressure tubing. A pressure gauge consisting of a transducer (IC Sensors Co., Model 93) and an indicator (Beijing Tianchen Automatic Instrument Factory, XS/A-1) with the accuracy of $\pm 0.01\text{MPa}$ were also connected to the reactor to observe the *in situ* pressure change of the system. The setup is shown in Figure 1. In the experiments, the reactor was placed in a constant-

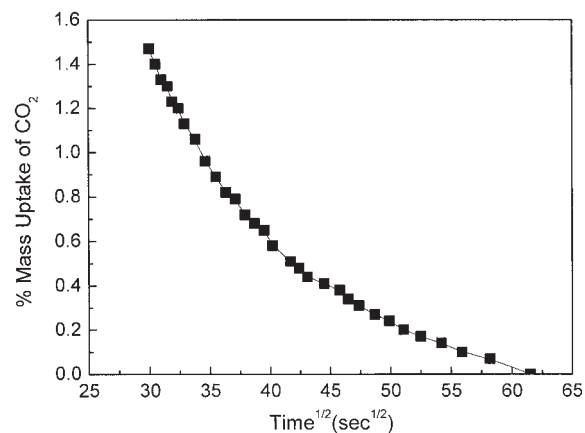


Figure 2 Mass uptake of CO_2 versus the square root of desorption time (temperature = 40°C , pressure = 10MPa , saturation time = 3h).

temperature circulator, which consists of a temperature control module (Thermo Haake, C10) and a bath vessel (Thermo Haake, P5). The fluctuation of temperature in the bath was less than $\pm 0.1^\circ\text{C}$.

Generation of foams

Foams were prepared in a glass tube ($\varphi 15\text{mm} \times 50\text{mm}$) inside the view reactor to facilitate removal of the foamed samples. PCL was placed into the tube, and

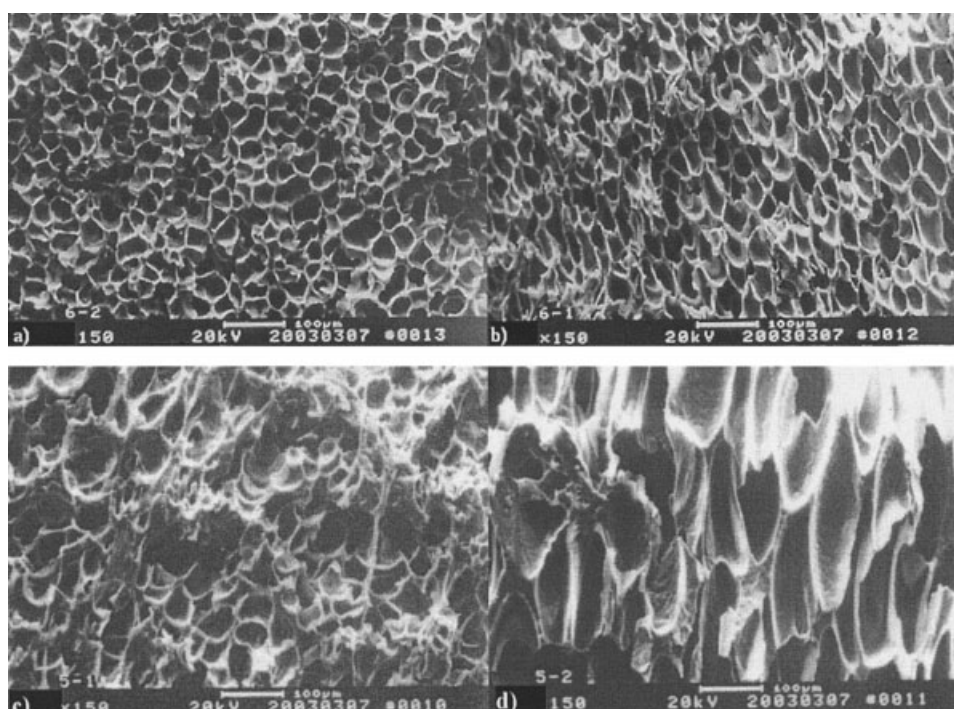


Figure 3 SEM photographs of cross and longitudinal sections of PCL foams (temperature = 40°C , saturation time = 3h , magnification = $\times 150$). (a) Cross section, pressure = 16MPa ; (b) longitudinal section, pressure = 16MPa ; (c) cross section, pressure = 15MPa ; (d) longitudinal section, pressure = 15MPa .

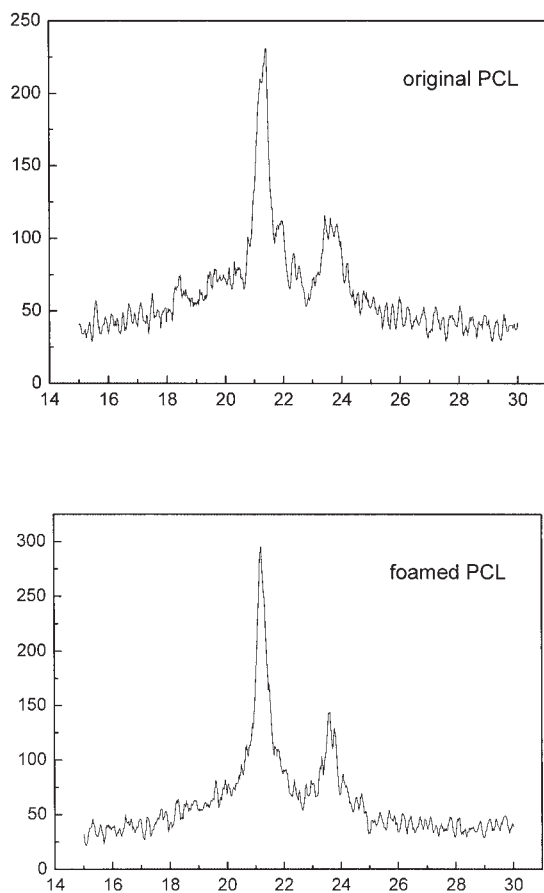


Figure 4 XRD results of original PCL and foamed PCL (temperature = 35°C, pressure = 10 MPa, saturation time = 24 h).

then they were put into the reactor together. The closed reactor was preheated in the bath to a certain temperature, which was manipulated by the heating system. Having been flushed for a few minutes with CO₂, the cell was filled up to the desired pressure. The resin then was exposed in SC CO₂ for a prescribed period of time. In the end the valve of the reactor was opened and the pressure was quenched rapidly to atmospheric conditions. The time of depressurization was recorded to study its influence on the final product. The system was maintained at zero pressure for approximately 0.5 h so that the bubbles could grow completely.

Foam characterization

The foams were characterized to determine their densities, cell sizes, and cell shapes. Density was measured using a gravity bottle with a capillary tube in its lid. The weight of the bottle filled with distilled water was measured with an analysis balance at a preset temperature. The sample then was put into the bottle, water of same volume as the sample overflowed along

the capillary tube. The bottle containing both water and sample, which was weighed and its density was calculated using the following equation:

$$\rho = w_1\rho_0/(w_1 + w_2 - w_3)$$

where ρ is the density of sample; ρ_0 is the density of water; w_1 is the weight of the sample; w_2 is the weight of the bottle filled with water; and w_3 is the weight of the bottle containing both water and the sample

Foamed samples were also observed with an AM-RAY-1000B scanning electron microscope (SEM). The samples were prepared by freezing in liquid nitrogen, fracturing the surface, mounting the fracture on stubs with carbon paint, and sputter coating with an approximately 100 Å layer of gold. Each cell size was calculated through eight diameter measurements and the average value is regarded as the cell diameter.

RESULTS AND DISCUSSION

Desorption kinetics

The desorption kinetics of CO₂ in PCL at a given set of processing conditions (40°C, 10 MPa) was studied with Berens' method.^{14,15} Through these measurements, average mass gain was calculated, and the results were plotted versus the square root of desorption time. In Figure 2 it can be seen that Fickian theory does not fit with the plots perfectly.

Morphology of cellular samples

SEM results demonstrated that treated PCL have the typical skin-core structure, though, unlike common microcellular foams, the cell sizes are more than 30 μm . It should be caused by the fact that the barrier force encountered during the nucleation process is quite subtle, since PCL is in the rubbery state under our experimental conditions. Figure 3 shows the SEM micrographs of the longitudinal section and cross sec-

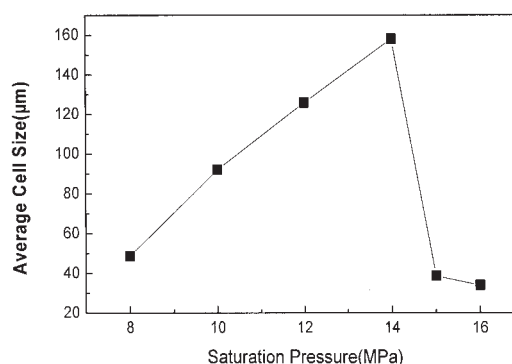


Figure 5 Average cell size as a function of saturation pressure (temperature = 40°C, saturation time = 3 h).

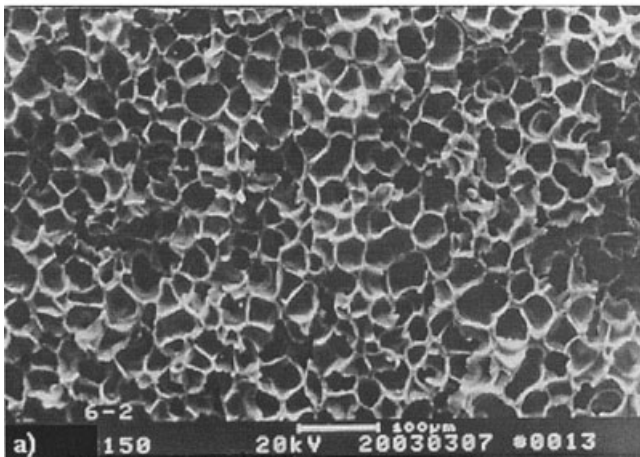
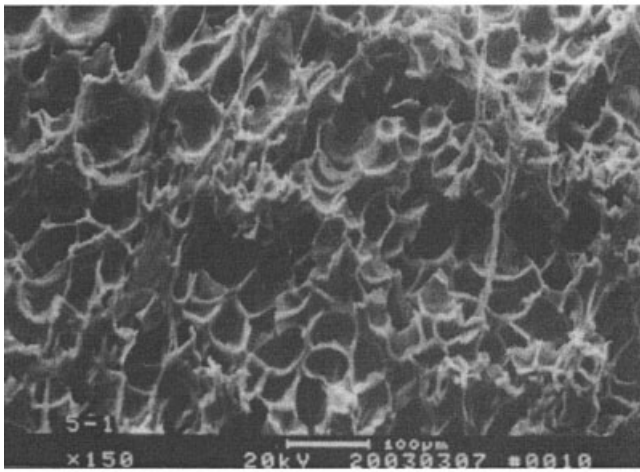
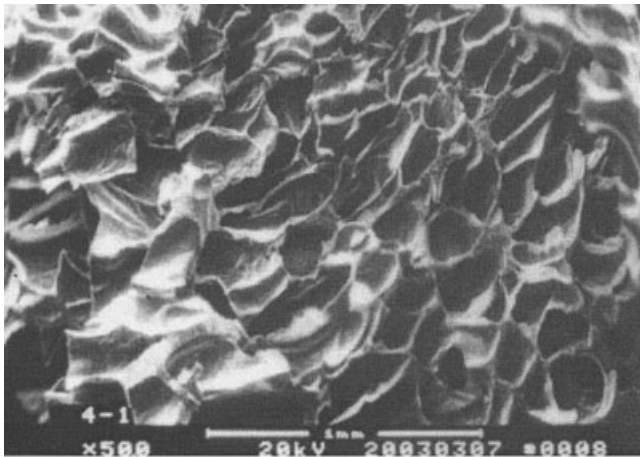


Figure 6 SEM photographs of cross sections of PCL foams foamed at different saturated pressures (saturation time = 3 h, temperature = 40°C, magnification = $\times 150/50$). (Top) 14 MPa; (Middle) 15 MPa; (Bottom) 16 MPa.

tion of foamed PCL. We can easily infer that, during the nucleation process, bubbles can't grow freely in the diameter direction because of the space limitation of the tube, in contrast to the complete growth of the cells in the length direction.

Crystallinity of the cellular samples

It has been shown that molar mass and crystallinity are the dominant factors effecting the biodegradability of PCL^{14,15} and the amorphous part of PCL degrades prior to the crystalline part in a biotic environment.^{16,17} As a result, X-ray diffraction was applied to study the crystallinity of virgin and microcellular PCL, as shown in Figure 4. It can be observed that, after foaming, intensity of the diffraction peak of the material increased compared to the original sample. This indicates that the crystallinity increased after foaming, so, compared to virgin PCL, the microcellular foam PCL is rather difficult to degrade.

Effect of pressure on foam structure

The effect of saturation pressure on the foam structure was studied at 40°C. The experimental results in Figures 5 and 6 show that the cell size first increases with saturation pressure until 14 MPa and then decreases from 14 to 16 MPa. As shown by homogeneous nucleation theory, when the magnitude of the pressure drop increases, the energy barrier to nucleation also decreases, leading to more cells nucleated in a given volume. Therefore, the cell size decreases with the increase of saturation pressure from 14 to 16 MPa. This homogeneous nucleation theory was also verified by Goel and Beckman.⁶ But how to explain the phenomenon at lower pressures, i.e., the final foam cell sizes show an inclination to increase with pressure? In this pressure range, since the pressure releasing gradient is less than that of high saturation pressure (14 ~ 16 MPa), its effect compared with the energy barrier is rather subtle. At the same time, fluid density as well as the amount of CO₂ in the system is crucial, so larger CO₂ bubbles form in the saturated PCL melt at higher pressure than at lower pressure.

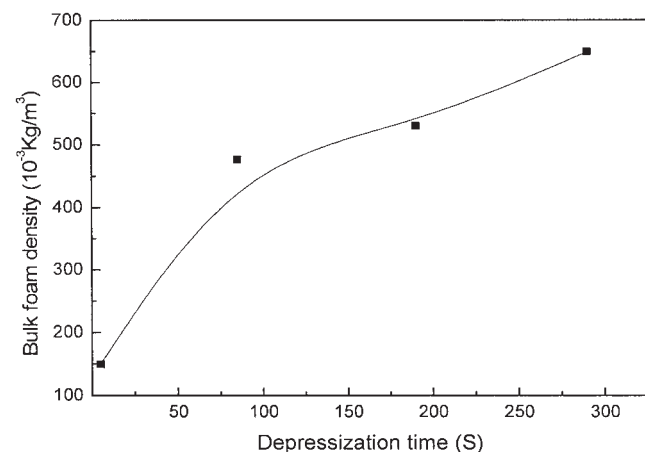


Figure 7 Density of bulk foams as a function of depressurization time (pressure = 10 MPa; temperature = 40°C, saturation time = 2 h).

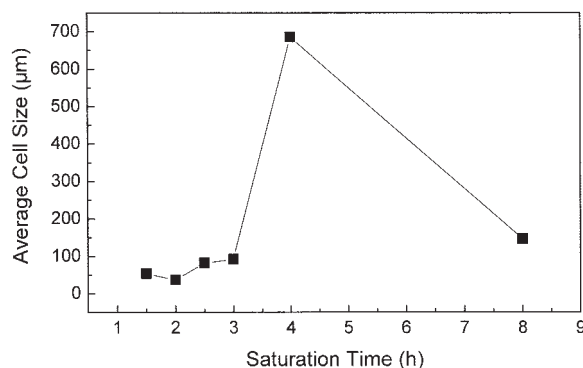


Figure 8 Average cell size as a function of saturation time (pressure = 10 MPa; temperature = 40°C).

Effect of depressurization rate on foam structure

A series of experiments were carried out at 40°C and 10 MPa with the depressurization rate varied. The experimental results are given in Figure 7, which shows that the bulk foam density increases with the depressurization time. It can be explained as follows: with prolongation of the depressurization time, cells had more time to contract at the fixed sites and the bulk volume decreased. Therefore, the bulk density increases with depressurization time.

Effect of saturation time on foam structure

The effect of saturation time of polymer with SC CO₂ has been studied at fixed pressure (10 MPa) and temperature (40°C). It can be seen from the experimental results shown in Figure 8 that the average cell size changes subtly at the beginning, from 1.5 to 3 h. The cell size then increases sharply from 3 to 4 h and decreases sharply from 4 to 8 h. Although pressure quench is a decisive factor on the foam structure, our study as well as Goel and Beckman's indicates that saturation time also has contributed to the foam structure. As explained by Goel and Beckman,⁶ the longer the polymer is exposed to the high-pressure CO₂, the greater the amount of CO₂ absorbed by the polymer. Here the SEM micrographs were taken in the central region of the samples, i.e., the influence of concentration gradient across the sample thickness was excluded. Therefore, only the influence of saturation time on the foam structure is considered in cell size

calculation. Theoretically the longer the time, the larger the cell produced. But for the decreasing phenomenon from 4 to 8 h, the mechanism needs to be further studied.

CONCLUSION

Foaming of biodegradable PCL in SC CO₂ and the various factors effecting the microcellular structure have been studied. Different saturation pressures result in different nucleation processes. In the lower pressure range, the final foam cell sizes show an inclination to increase with pressure, while the opposite result is observed in the higher pressure range. The bulk density of foam also increases with a decrease of depressurization rate. Saturation time is another decisive factor governing the structure of the product.

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