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Fabrication and analysis of dual-scaled shape memory foam

Hyung Min Kim[a], Zheng Min Huang[a], Ji Sun Kim[a], Jae Ryoun Youn[a,*], Young Seok Song[b,*]

[a] Research Institute of Advanced Materials (RIAM), Department of Materials Science and Engineering, Seoul National University, 56-1, Shinlim-dong, Gwanak-gu, Seoul 151-744, Republic of Korea
[b] Department of Fiber System Engineering, Dankook University, 126 Jukjeon-dong, Suji-gu, Yongin-si, Gyeonggi-do 448-701, Republic of Korea

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ABSTRACT

We analyzed dual-scaled shape memory polyurethane foams that recovered from the compressed shape to their initial dimension at above the transition temperature. Such a recovery leads to an enhancement in the thermal features, especially thermal resistance. Dual scale shape memory foams were fabricated by using the salt leaching method, and their internal structure was analyzed. The porosity and interfacial thermal resistance of the dual scale foam were enhanced significantly, which led to the excellent thermal resistance. The thermal behavior of foamed materials was modelled analytically. The enhancement in mechanical properties was induced by the dual size pores. In addition, thermo-mechanical properties of the shape memory foam, such as shape recovery, shape fixity, and shape repeatability, were characterized.

1. Introduction

Interest in insulating materials has increased since an effective insulating material plays a key role in saving energy and reducing carbon dioxide production. In particular, polyurethane (PU) foams have been used in many insulation applications due to their low thermal conductivity and good processability [1–3]. PU is generally composed of hard and soft segments, and their thermodynamic incompatibility results in a phase separated structure. Hard segments formed by hydrogen bonding with dipole-dipole interaction affect the crystallization below the melting temperature and soft segments act as a reversible phase controlling the shape memory effect [4–10]. Due to the thermo-elastic phase transformation, PU is used as a shape memory polymer (SMP) which can be deformed in response to external stimuli such as heat, light, moisture, pH, and electric field. The shape memory materials have received significant attention recently [11–16]. For instance, shape memory alloys (SMAs) such as copper-aluminium-nickel (Cu-Al-Ni) and nickel-titanium (NiTi) alloys show superior shape memory performance and good stability. However, their manufacturing processes are complex and expensive [17–19]. On the other hand, shape memory polyurethane (SMPU) has been recognized as a fascinating shape memory material due to its excellent properties including a wide temperature range for shape recovery (-30 to 70 °C), high shape recoverability, easy processing conditions, and low cost compared with SMAs [20–23]. Moreover, the SMPU can be controlled by changing the molar ratio of hard segments to soft segments, molecular weight of soft segments, and polymerization process [24–26].

Two different blowing agents have usually been adopted for foaming of the SMPU, i.e., chemical blowing agent and physical blowing agent [27–29]. The salt leaching method was used in this study to produce a new foam structure with dual scale pore sizes [30]. The dual scale PU foam showed strong shape memory behavior, and significant enhancement was found in the thermal and mechanical performance of the foam. Theoretical analysis for heat transfer and numerical modeling for mechanical response of the SMPU foam were carried out and compared with experimental results.

2. Experimental

2.1. Synthesis of SMPU

A mixture of poly caprolactone diol (PCL diol, $M_n = 4000$ g/mol, Perstop) and 4,4′-diphenylmethane diisocyanate (MDI, Junsei Chemical) was reacted in a four neck cylindrical flask with continuous mechanical stirring under nitrogen atmosphere at 80 °C for 3 h to prepare a prepolymer. 1,4-Butanediol (BD, Sigma Aldrich) was added into the prepolymer as a chain extender for controlling the degree of polymerization. The SMPU obtained by the prepolymerization method was dried at room temperature under vacuum to remove the solvent and hardened further at 100 °C in an oven for morphological stabilization (Scheme 1).

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* Corresponding authors.
E-mail addresses: jaeryoun@snu.ac.kr (J.R. Youn), ysong@dankook.ac.kr (Y.S. Song).

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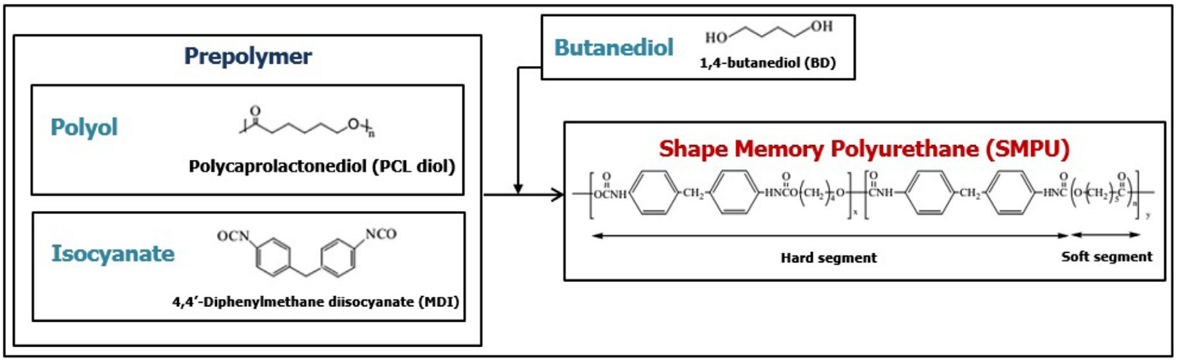

Scheme 1. Schematic diagram of the synthesis of shape memory polyurethane (SMPU) by prepolymerization method.

2.2. Fabrication of SMPU foam

The processing procedure for the SMPU foam is described schematically in Fig. 1 First, SMPU pellets were dissolved in tetrahydrofuran (THF, Daejung Chemicals) and a 25 wt% solution of SMPU in THF was prepared. Sodium chloride (NaCl, Daejung Chemicals) particles were ground and filtered by several micro glass filters with pore sizes of 100, 200, and 400 μm to control the pore size of the SMPU foam. Filtered NaCl particles were added to the SMPU solution at a volume ratio of 8–10 and SMPU/NaCl composites were prepared by using the different particle sizes of NaCl. The mixture of SMPU/NaCl particle was dried at 40 °C for 3 days to remove the THF completely. In order to leach NaCl

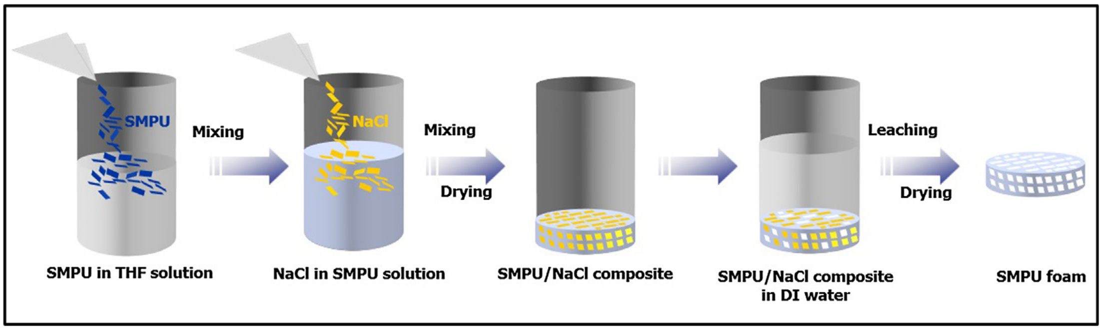

Fig. 1. Processing procedure for preparation of SMPU foams.

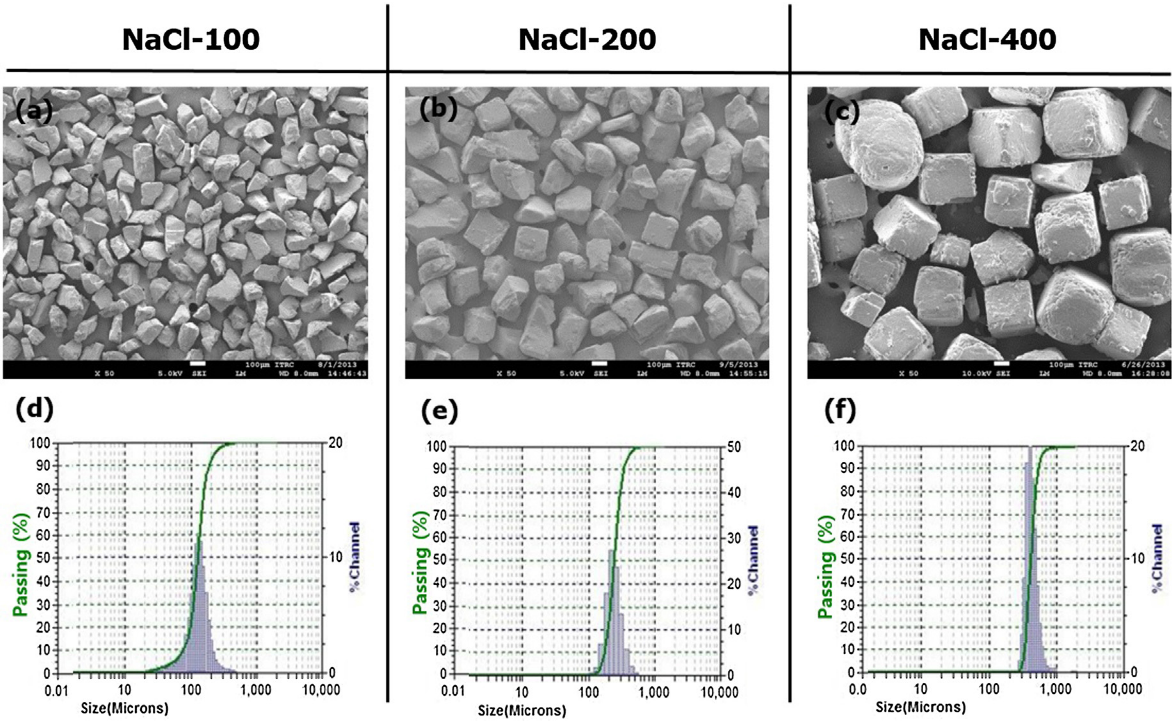

Fig. 2. Size analysis of filtered NaCl particles: (a) glass fiber with a size of 100 μm, (b) 200 μm, and (c) 400 μm. The corresponding particle size distributions of the filtered NaCl particles are presented. The average particle sizes of the NaCl were (d) 127.5, (e) 242, and (f) 413.8 μm.