Abstract

Four-dimensional (4D) printing, is a process of using smart materials in additive manufacturing enabling the creation of objects that dynamically change shape, size, or other attributes over time in response to external stimuli such as temperature, humidity, electric current, etc. In this study, we proposed and compared two novel thermo-mechanical programming processes for fused deposition modeling (FDM) of polylactide-based shape memory polymers (SMPs). The first programming i.e. programming during printing (PDP) process achieved a shape recovery ratio (R_r) of up to 99% for 4 mm thick samples, significantly outperforming the second programming i.e. programming after printing (PAP). Statistical analyses, including Levene's test and t-tests, further confirmed the significant differences in R_r and shape memory index (SMI) between the two methodologies. Through a comprehensive parametric analysis, optimization of shape memory thermal variables and mechanical properties is achieved for three different print orientations (flat, on edge, and upside) using response surface methodology (RSM). Further, a parametric study and optimization of the printing process parameters are achieved considering a systematic design of experiments (DoE) approach combining definitive screening design (DSD) and RSM with desirability functional analysis (DFA). Additionally, the effects of various infill densities (20% and 100%) and types (e.g., gyroid, concentric, grid, etc.) on shape memory properties and optical transmissivity were investigated. At 20% infill density, the gyroid pattern exhibited an R_r/R_t (shape recovery ratio to recovery time) of 30.37, indicating high efficiency in shape recovery. In contrast, at 100% infill density, these values were lower, reflecting longer actuation times despite improved total recovery percentages. Optical transmissivity varied significantly with different infill patterns and densities, suggesting potential applications in programmable thermo-responsive steganographic and encryption devices. For instance, optical power intensity measurements with white light and He-Ne laser sources demonstrated distinct variations in optical transmissivity corresponding to different infill configurations. These advancements highlight the remarkable potential of 4D printing in creating programmable, responsive materials with broad applications in smart manufacturing, photonics, and robotics. By integrating low-cost FDM 3D printing techniques, testing setups, innovative programming methodologies, and comprehensive characterization, this research provides a robust framework for enhancing the efficiency, effectiveness, and accessibility of 4D printing technology.

Keywords: 4D printing; Smart materials; FDM; SMP; Additive manufacturing; 3D/4D printing; Optimization