Chapter 1
Fundamentals of Four-Dimensional (4D) Printing

ABSTRACT

This chapter provides some examples that illustrate the potential of the concept of four-dimensional printing. The examples are chosen to illustrate the generalized definition of the fourth dimension within the technology. The exposition starts by introducing the general concepts that evolved out of all printing polymeric materials. Therefore, the authors provide illustrations of the concept of material morphing which stands at the core of the conventional definition of 4-D printing. Following such an illustration they discuss another emerging definition that casts 4-Dimensional printing in terms of layer-by-layer functional gradients. Such a definition, which is the future of this particular aspect of AM, is well suited for the printing of metallic objects. It is based on functional customization of material properties within each printer layer to ensure a pre-planned behavior of the printed structure upon the application within its intended environment.

INTRODUCTION

The ability of additive manufacturing, and especially printing, to construct an object in situ from its basic ingredients is a powerful trait. Perhaps it is the most fundamentally promising aspect of the technology. Thus, despite the current technological challenges that the field is undertaking, upon maturation, the ability to materialize an object that is custom built releases the true promise of the technology. This is likened to constructing some entity with customized DNA customization, not only allows for tailoring the shape, but also permits intentional modifications of behavior and response. In materials, and objects, this translates into intentional construction with respect to function. That is, to tailor the building blocks of the object to provide a precalculated behavior that is linked to the function or the functional environment of the object. The customization process may also guide the evolution the behavior of the object, through engineering its fundamental ingredients, revolve around a predetermined path. This path could be a property, response to an energetic stimulus, change of shape, or even simple endurance limit and hostile environment.

Analyzing this potential, true customization, is in essence an extension of the flexibility of additive manufacturing towards raw materials. The technology is almost material blind in the sense that it can process any material provided that the material is available in an appropriate form. Throughout the previ-

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ous chapters, there have been examples of processing a wide spectrum of materials (both type, class, and shape). These included ceramics, metals, biological tissue, high-energy yield materials, nanomaterials, etc. in metal AM, we have surveyed the wide variety of available processes that allow for processing any type of metal or alloy at different scales (nano-to macro) in the building block-by-building block sequence. In all, the potential for customization, and guiding the evolution of the ingredients of an object along the pre-determined path, adds a fourth dimension to the processed object. Such an addition, is of recent origin (few years) and is the origin of the now familiar term "4-D printing". Four-dimensional additive manufacturing manifests the core of the future path in the field. Although being mostly within laboratory domain, it is worth exploring at this early stage. This is because of the pace by which the ideas involved are progressing, and maturing, along with the level of activity currently taking place in the discipline.

Initially, 4-D printing was conceived as a path to implement objects with self-response. This response, or morphing, would result from a trigger (or stimulus) that would cause the material of the object to react. This action, if precisely precalculated, would cause the shape of the printed object to morph in time. As such, when the term 4-D printing was initially coined, it was defined as: 4-D printing is the 3-D dimensional printing (standing for the familiar geometrical space indicating the volume of an object) in addition to time as the fourth dimension (since the morphing or evolution shape is a function of time) (Tibbits, 2013, 2014; Tibbits, et. al., 2014; Ge, et., al., 2013; Pei, 2014). The concept of time morphing is illustrated in Figure 1. The figure shows a 3-D forming structure, printed from a "smart" shape memory polymer (SMP).

SMP denote a class of digital materials with time-dependent thermally activated shape morphing. They can recover the permanent shapes from a single (or multiple) programs temporary shapes upon application of a suitable stimulus. This stimulus may be thermal, magnetic field, or light. Morphing of shape in this class of materials stems from the ability to sense ambient changes and react to the changes in predetermined sequence. This class of materials may also be chemically to achieve predetermined levels of biocompatibility, and biodegradability. The materials are formed by mixing two bays materials at specific ratios on a digital voxelized domain achieve prescribed thermomechanical and shape memory behavior.