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Technical Paper

Indirect additive manufacturing based casting of a periodic 3D cellular metal – Flow simulation of molten aluminum alloy

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ABSTRACT

Direct-metal additive manufacturing (AM) processes such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) methods are being used to fabricate three dimensional (3D) metallic mesostructures with a laser or electron beam over metal powder beds. In spite of their good manufacturability on 3D network structures, the direct AM processes still appear to have disadvantages – limited selection of materials, high thermal stress traced to the high local energy source, poor surface finish, anisotropic properties, and high cost on powder materials and manufacturing with high power beams. As an alternative method to manufacture 3D network cellular metals, we suggest and implement an indirect AM method combining an inkjet 3D printing of wax and metal casting – Indirect AM based Casting (I·AM Casting). Due to the high surface area of the cellular structural mold exposed to an ambient temperature during casting, flow and solidification of a molten metal appear to be a strong function of temperature. Therefore, viscosity, density, and thermal conductivity of a molten metal and mold may need to be provided as a function of temperature for characterizing flow and solidification. The objective of this study is to test the hypothesis that casting of a molten metal into a cellular structural mold is highly sensitive to temperature that temperature-dependent viscosity, density, and thermal conductivity should be implemented for the simulations on flow and solidification of a molten metal. A transient flow and heat-transfer analysis of a molten aluminum alloy, AC4C, is conducted through a 3D cellular network mold made of zircon. Solidification of AC4C through the cellular structural mold during casting is simulated with temperature-dependent properties of the molten metal and mold over a range of running temperature using a user defined function (UDF) of ANSYS/FLUENT. We found that solidification is sensitive to viscosity and thermal conductivity of AC4C and the zircon mold, which are a strong function of temperature. The simulation with constant thermal and physical properties of AC4C and the zircon mold overestimates the solidification time with an error of 20% compared to the one with the temperature-dependent properties.

1. Introduction

Cellular metals are increasingly receiving attention due to their combinations of mechanical, thermal, and acoustic properties that provide potential opportunities for diverse multifunctional structural applications. Particularly, they have high specific strength [1,2] and high specific strain [3–5], excellent impact absorption [6,7], acoustic insulation [8], and heat dissipation media and compact heat exchangers [9].

Several manufacturing methods of cellular metals have been used: Stochastic metal foaming features to form gas in liquid metal or to mix metal powders with a blowing agent which are then compacted and melted [10]. In spite of their high stiffness-to-weight ratio, lack of control of cell-topologies with the stochastic metal forms still limits a variety of high performance engineering applications. Manufacturing of *periodic cellular metals*, which are excellent in controlling mechanical and thermal properties, have been explored as well. For example, 2D honeycombs have been manufactured by stamping thin sheets at high temperature into a corrugated shape and then joining them to create periodic structures [1]. Alternatively, they have been built by joining and bonding slotted metal sheets [1], forming/punching [11], thermo-chemical extrusion [12], electro-discharge machining [13] and weaving and brazing metal filaments to form a 3D periodic textile [14]. Even though 2D and limited 3D cellular topologies can be manufactured, *freedom of manufacturability of 3D cellular structures is still limited in*

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that a whole manufacturing set-up should be redesigned/rearranged whenever the cellular geometry varies.

Recently emerging 3D printing technologies [15–19] appear to help relatively freely manufacture 3D cellular geometries. Direct-metal additive manufacturing (AM) processes which use a laser or electron-beam over a metal power-bed are capable of manufacturing fully complex 3D cellular metals. Selective Laser Melting [20], Electron Beam Melting [21], and Direct-Metal Laser Sintering [22] are the available direct AM processes to fabricate 3D metallic cellular structures. Notwithstanding AM's capabilities to fabricate parts with complex cellular geometries, there are still several constraints in the process, which limits parts' scalability to structural applications. For example, selection of materials is limited: e.g., aluminum alloys are challenging to process due to high thermal conductivity and high optical reflectivity [23]. Fabricated parts suffer from thermal residual stresses [24]. The 1D energy based patterning mechanism induces poor surface finish and anisotropic properties of parts caused by the combined effects of powder size and the power/feed speed of laser or electron beam [25]. In addition, cost on powder materials and manufacturing with high power beams still remains high with the direct-metal AM processes. For these reasons, it may be argued that *direct-metal AM methods are not capable of fabricating cellular structural parts at a sufficient scale for structural applications.*

As an alternative way to manufacture 3D cellular metals, which can overcome the disadvantages of the direct-metal AM techniques, polymer AM methods may be used by combining with metal casting. We may call this "Indirect AM based Casting (**I·AM Casting**)". I·AM Casting can expand the selection of materials, e.g. aluminum and magnesium cellular structures, with proper design of gate systems related to control casting of a molten metal. I·AM Casting can produce *an isotropic property of cell walls* and produce good surface finish. Obviously, I·AM Casting can fabricate parts to have a customized design. More importantly, this method also enables one to carry off mass-production with clustering of cellular patterns, which will accelerate the net processing speed with multiple parts. These all provide one with the potential to scale up the cellular metals to their structural applications with relatively cheap cost due to their *mass-production combined with reduced cost of pattern fabrication using automated 3D printing technologies*.

In spite of the scalable potential of periodic cellular metals to structural applications, the manufacturing methods of I·AM Casting for cellular metals have not been actively explored and were not fully understood. A few qualitative studies of I·AM Casting have been reported: A tetrahedral Be-Cu alloy lattice structure, with a cell size of 10 mm, was fabricated by an investment casting of an ABS sacrificial cellular pattern printed by a Fused Deposition Modeling (FDM) method [26]. Recently, a 3D lattice shaped mold built by 3D printing sand powder was used for metal casting [27]. It demonstrated an excellent mold printing technique, however, the casting in the proposed method still appears to provide many defects caused by network structures with sharp corners of lattice structural molds that may prevent fluid-flow and undesired solidification, resulting in misrun and porosity, which shows a need of extensive quantitative studies on indirect AM.

Quantitative studies on the indirect AM method have not been aggressively explored due to their highly complex and multidisciplinary problems across the process–continuum modeling (thermal stress, flow, heat transfer, and water diffusion) with multiple materials (polymers, metals, and ceramics) for multiphase–solid, liquid, and gas. As an initial step to fully understand the flow of a molten metal in a cellular structural mold, we conduct a quantitative study on I·AM Casting.

The objective of this paper is to investigate the flow of a molten metal though a 3D network-shaped cellular structural mold. Solidification of a molten aluminum alloy, AC4C combined with transient heat transfer will be modeled and experimentally validated. Temperature-dependent properties – viscosity, density, and thermal conductivity will be used for simulation on flow and solidification of the casting in the cellular structural mold.

2. Experimental

In this section, we will briefly describe a hybrid manufacturing procedure carried out through additive manufacturing of 3D sacrificial network patterns, followed by a traditional investment casting.

2.1. Design of a sacrificial pattern

A computer aided design (CAD) model for a sacrificial pattern of a 3D cellular solid is generated with commercial software, Pro-E. An arbitrary complex 3D cellular structure is selected for a conventional 3D printing process. The volume of interest, shown in the dotted line in Fig. 1(a), represents a 3D auxetic hexagonal cellular solid with a negative Poisson's ratios. We will not cover its mechanical properties, e.g., effective modulus and effective Poisson's ratio, of the final product in this paper, which is beyond the scope of this manufacturing work. The readers who may be interested in the mechanical properties of the cellular structure are referred to the articles [2,3,28–32].

The final metallic product with the complex cellular pattern is challenging to fabricate with the suggested I·AM Casting due to the expected difficulties of metal-flow associated with a sudden change of flow direction (Fig. 1(a)). This is the reason for selecting the complex cellular pattern to investigate manufacturing defects through I·AM Casting, which will be used for further discussion on the defects with numerical analysis of metal-flow in Section 3.

2.2. Production of a sacrificial pattern with an additive manufacturing method

Due to the complex shape of the cellular structural pattern in Fig. 1(a), we may not be able to use the conventional pattern tooling methods. In this study, we use an additive manufacturing method to build a sacrificial pattern. 3Z VX200 system (Voxeljet) is used to print the 3D cellular sacrificial pattern. A CAD model is transferred to the 3D printing system to fabricate the 3D cellular structural pattern. Plastic fine powder materials, each with a diameter about 45 μm, are prepared by a spreader and selectively printed layer by layer with a high performance inkjet print-head having a printing resolution of 250 dpi (100 μm). PolyPro, a polymethyl methacrylate (PMMA) type polymer infiltrated with wax, is used for the base material of 3Z VX200. The base material burns out almost ash free and forms dense and smooth surfaces. Fig. 1(b) shows a printed cellular pattern with the 3Z VX200 system. The measured wall thickness of the pattern was 1.247 ± 0.059 mm. Due to the limited printing resolution, the fabricated wall thickness was rather thicker than the desired one in the CAD model. We use the printed dimension for the simulation of casting in Section 3.2.

2.3. Pattern assembly

For a laboratory scale experiment, two cellular solid patterns are considered to be assembled with a gating system consisting of a pouring cup, sprue, runners, and gates (Fig. 2). In the lighter and oxidizable metals such as aluminum and magnesium, drossing and air entrapment are known as severe problems resulting from turbulent pouring primarily caused by a top gating [33,34]. Therefore, a bottom gate system, which is recommended for avoiding turbulence, is applied in this study [33,34]. Fig. 2 is the suggested bottom gate system consisting of a pouring cup, sprue, runners, and gates.