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Procedia CIRP 67 (2018) 504 – 509
www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17

Logistic regression and response surface design for statistical modeling of investment casting process in metal foam production

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Abstract

A metal foam represents a promising material since it keeps the high mechanical properties of the metal while reducing the weight up to 90%. Among several manufacturing processes, the investment casting is a foundry process flexible enough to be suitable both for stochastic and for regular foams. This paper presents an experimental determination of the manufacturing process of metal regular foams by investment casting. The goal is to derive experimentally an actual "formability map". The use of logistic regression and response surface design is proposed as an effective tool for determining a statistical model of the metal foam casting process.

Keywords: Metal foams; Logistic regression; Generalized linear models; Design of Experiments (DoE)

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1. Introduction

The terms cellular metals, or porous metals, are general expressions referring to metals having large volume of porosities, i.e., with pores deliberately integrated in their structure. These materials have low densities and novel physical, mechanical and thermal properties. They are potential materials for lightweight structures, for energy absorption and thermal management applications. They can be divided into closed and open cell structures.

In this paper, the open cell structures are treated. The typical applications of this material are catalytic supports, heat exchangers, filter elements, acoustic absorbers, crash absorbers, etc., because they have special properties, such as the permeability of the open cell structure, high porosity and high ratio of surface area to volume.

When the porosity cannot be subdivided into well-defined cells, the material is usually referred to as *metal sponge*. On the other hand, the terms foamed metal or *metal foam* apply to porous structures whose solid matrix has a large fraction of interconnected, homogenous and *regular* open cells [1].

The open cell metal sponges and foams can usually be made by a foundry process (e.g., sand-casting). The process relies on the casting of the metal around a preform of particles that defines the shape of the porosity in the final material [2]. After cooling, the preform can be removed by solvent leaching. A popular use of this technique utilizes salt (NaCl) as a space holder to produce aluminum sponges and foams [3]. NaCl has several advantages such as being readily accessible, non-toxic and can be removed from the foam by dissolution in water. By having a melting point of 801 °C, it can be used with metals that have a melting point lower than this value.

Substitution of NaCl with higher melting point materials also permits the production of foams from higher melting point metals [4]. This may include other water-soluble materials, or insoluble ones including different types of sand. In this form, the process becomes more like conventional sand-casting processes.

The pore size and porosity of the foam can be varied through selecting appropriate geometry of particles. For example, the Kelvin's structure is considered as a model metal foam with homogenous and regular open cells [5]. To produce this kind of metal foams by sand-casting process, a preform is build by stacking of shaped plates, each containing several polyhedrons. These plates are made of agglomerated sand.

doi:10.1016/j.procir.2017.12.252

In general, the infiltration/sand-casting process is simple and with low cost because of the relatively cheap raw materials and simple processing equipment. However, the metal foams produced by this process have a low porosity, only from 50% to 80%.

Metal foams can also be fabricated without directly foaming the metal. The investment casting (a.k.a. lost-wax casting), in which the material is poured into a ceramic cavity designed to create an exact duplicate of the desired part by means of soluble preforms (wax patterns), can also be used as manufacturing process for metallic foams. The ceramic cavity is obtained by investing (surrounding) the wax patterns of a refractory material. The fragile wax patterns must withstand forces encountered during the mould making.

Aluminum alloys are usually used in investment casting mainly due to their high fluidity, but other metals can also be processed. The densities and foam morphologies are of course determined by the preforms. Porosities typically range from 80 to 97%. The investment casting is a foundry process flexible enough to be suitable both for metal sponges (stochastic foams) of sub-millimetric pore size and for periodic (regular) foams with pore sizes of several millimeters.

In the research activity carried out at the University of Salento, an investment casting process was considered in order to produce aluminum alloys foams with homogeneous and regular open cells. Examples of metal foams obtained by in the research are depicted in Fig. 1.

The present paper presents an experimental determination of the investment casting process of metal foams with homogeneous and regular open cells, which are employed as catalytic supports. Basically, catalytic metal foams have to offer low resistance to thermal transport [6], low resistance to mass transfer [7] and needs to be easily coated with a catalytic layer on their surface via dip coating or other loading methods [8]. In this kind of applications, the geometrical characterization of produced metal foam assumes a primary importance. The goal of our research is to derive an actual “formability map” of the investment casting process based on the geometric characteristics of the produced metal foam.

The remainder of the paper is organized as follows. In section 2, the investment casting process is detailed. Section 3 describes the experimental procedure implemented. In section 4, a statistical model of experimental data is presented, while in section 5 the actual results are discussed. Finally, conclusions are provided in section 6.

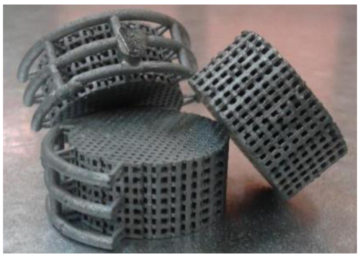

Fig. 1. Example of cylindrical metal foams obtained by investment casting.

2. The investment casting process

In this section, a technique to manufacture metal foams by investment casting is discussed. The starting point is a polymer foam used as prototype (a.k.a. wax patterns). In our work, the polymer foam was processed into a structure with open pores by an additive process (3D printing).

The next step consists of embedding the resulting foam with a special slurry of heat resistant (refractory) material, e.g., a mixture of mullite, phenolic resin and calcium carbonate (plaster). This material is water-soluble and capable of withstanding the temperature of the molten metal under vibrating and tapping.

After embedding, the mould is dried and then baked to harden the embedded material and to decompose (and evaporate) the polymer foam, leaving behind a negative image of the foam. This mould is subsequently filled with molten metal in hot state under a moderate pressure. After solidification and cooling, the mould materials are removed (e.g., by water under high pressure), leaving the metal foam which is an exact image of the original polymer prototype.

A detailed description of the process is presented in the following subsections.

2.1. Polymer foam preparing

A polymer prototype with the desired cell size, and relative density was selected first (Fig. 2). It will be soaked in some organic liquids for minutes before using it as a template, which is helpful to infiltrate the mould obtained from pouring plaster slurry into this foam hereafter by molten metal.

Once a prototype is produced, it is assembled with other components: the runners and sprue gating, to form a casting cluster or assembly (see Fig. 3). The sprue gating is provided by a gate, i.e., the location at which the liquid metal enters the mould cavity.

2.2. Plaster slurry

The entire assembly is then dipped in a plaster slurry (Fig. 4). Since there are some reactions shrinkage and phase transition shrinkage the plaster while it is being dried and baked, cracking and corresponding strength decreasing of the plaster mould will be induced.

Also, it is difficult for plaster to be dissolved in water because the solubility of calcium carbonate in water is limited. So, in order to obtain strong and soluble mould, it is necessary to add some kinds of other materials into the plaster. Mullite and phenolic resin are typically used to increase the strength and solubility. In addition, the agitation during the preparation of plaster slurry is necessary for homogenization.

The speed should be appropriate, because very high speed will induce the slurry spray and gas dissolution to decrease its strength. On the contrary, very slow speed will make it inhomogeneous.