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Design of Honeycomb Structures Produced by Investment Casting

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Abstract

Investment casting combined with the additive manufacturing technology enables production of the thin-walled elements, that are geometrically complex, precise and can be easy commercialized. This paper presents design of aluminium alloy honeycombs, which are characterized with light structure, internal parallel oriented channels and suitable stiffness. Based on 3D printed pattern the mould was prepared from standard ceramic material subjected subsequently to appropriate heat treatment. Into created mould cavity with intricate and susceptible structure molten AC 44200 aluminium alloy was poured under low pressure. Properly designed gating system and selected process parameters enabled to limit the shrinkage voids, porosities and misruns. Compression examination performed in two directions showed different mechanisms of cell deformation. Characteristic plateau region of stress-strain curves allowed to determine absorbed energy per unit volume, which was 485 or 402 J/mm^3 depending on load direction. Elaborated technology will be applied for the production of honeycomb based elements designated for energy absorption capability.

Keywords: Investment casting, 3D printing, Honeycomb, Light structures

1. Introduction

The cellular metal structures have already found their application in automotive, aviation and energy industry due to the high specific strength, excellent impact and acoustic absorption and good heat dissipation. Among several manufacturing methods the investment casting allows manufacturing of thin-walled complex shapes with excellent surface and dimensional accuracy. Produced final parts can be practically applied after minimal finishing and machining of only gating system is necessary. Moreover possibility to create complex mould cavity without standard cores designates this method for production of periodic structures like honeycomb. These structures are manufactured by extrusion of metal alloys or by bonding of metal sheets which next are stretched to spatial form [1, 2]. Casting process based on 3D printed pattern can be very versatile and rapid way for designing of prototypes of complex parts like honeycomb structures. Tian Lei et al. [3] using stereolithography-assisted investment casting optimized design of metal heat transfer device. By changing topology of the heat sinks they quickly examined different type and configuration of structures. It was possible to produce complex metal part with developed surface and shape like a bio material. Designed pattern with gating system can be produced by the means of several available additive manufacturing processes. The technology of Fused Deposition Modeling (FDM) is one of the most common additive methods and products made on the basis of this technology are built on a layer-by layer basis, through a series of cross-sectional slices. The major advantages of 3-D printing as compared to injection moulding or machining/subtractive technologies are: relatively inexpensive 3-D printers, no need for expensive tools like moulds or punches, ability to easily share designs and outsource manufacturing, custom products in small quantities produced with the reasonable price. Printed pattern can be subsequently utilized to form a mould cavity during burnout cycles of investment casting. Thus, in relatively convenient process the metal honeycomb structures, which exhibit high strength and stiffness can be produced. The compressive strength of honeycomb materials is the topic of many scientific publications. Such regular cellular structures are generally investigated by acting static or dynamic compressive forces, which can be applied horizontally or vertically. Piekło et al. presented the study on perpendicular loading of the cells of honeycomb samples manufactured by investment casting with 4xxx.0 alloy [4]. The FEM numerical simulation was also performed, supporting the experimental trial. As concluded the presence of casting defects such as misruns or gas porosity significantly deteriorates the cohesion forces within the cellular structure.

In this paper elaborated investment casting based on 3D printed pattern for manufacturing of cellular structures is presented and discussed. Investigations of the physical phenomena during deformation of cast honeycomb elements under compression load confirmed their good properties and benefits of the process.

2. Experimental procedure

Manufacturing process comprises printing of pattern, moulding, heat treatment of the mould and metal pouring under low pressure. The honeycomb structure was designed in Autodesk Inventor Professional 2018. The Simplify3D software was applied in order to create the G-code file. Spatial model from polylactide (PLA) was produced with the use of HBOT 3D printer. The layer height was 0.2 mm, the nozzle diameter was 0.6 mm and the printing rate was 3600 mm/min. Subsequently, the pattern was mounted in perforated flask and overflowed with plaster slurry prepared from Gold Star xxx investment powder. Water/powder ratio was 40:100. After hardening, the mould was subjected to heat treatment, effecting in the entire evaporation of the polylactide, leaving the intricate cavity of its shape. Preheated mould to 400°C was mounted in autoclave and under the pressure of 0.04 MPa molten aluminium AC 44200 alloy (Si-10,5%-13,5%; Fe-0,55%; Cu-0,05%; Mn-0,35%; Zn-0,10%; Ti-0,15%; Al-rest) was poured into the cavity through special gating system. Honeycomb specimens of 36x37x20 mm were examined at room temperature applying compression testing at the Tinius Olsen H25KT testing machine.

3. Discussion of test results

Critical process parameters for casting quality were: low pressure, geometry and position of gating system as well as pouring of aluminium alloy and mould temperature. Often observed perforation of thin walls could be caused by gas entrapment (see Fig. 1). At the insufficient pressure (vacuum) or low pouring temperature of the alloy the mould was incompletely filled with the Al alloy and misruns in thin walls were observed (see Fig. 1b). It can be concluded that all parameters should be precisely controlled and sometimes several experimental attempts are needed to produce sound cellular casting, especially at supposed hot spots (see. Fig. 1c).

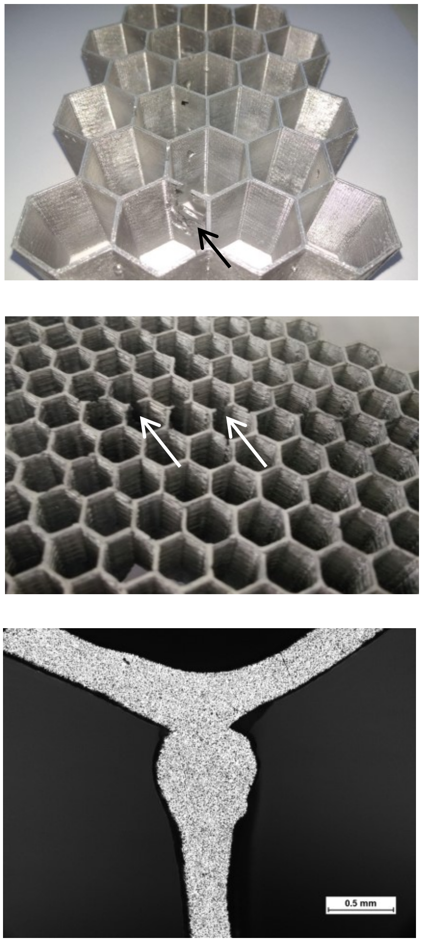
a)
b)
c)


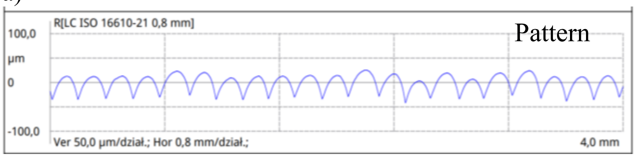
Fig. 1. Perforated walls of incorrect cast honeycomb (a, b), the connection of the three walls (c)

Mun et al. [5] analysing flow simulation of molten aluminium alloy in 3D cellular shell explained that excessive gas inclusion results from turbulent flow at sudden change of direction near the gate. On the other hand the authors of presented paper observed rather decrease of low pressure at the top of mould and then arising of defects during solidification. Generally, proper gating system providing effective Al alloy feeding during entire cast process combined with correct process parameters allow to produce sound casting of honeycomb elements with wall thickness of 0.5-1.0 mm. Another specific feature of cast elements produced on the base of pattern printed layer by layer is roughness and shape accuracy. Unfortunately, used Fused Deposition Modelling has disadvantages, such as lower precision in comparison to other technologies, reduced choice of materials, surface quality, and large anisotropy of mechanical properties [6, 7]. To minimize the anisotropy and improve the mechanical properties of FDM printed samples, the low molecular additives can be added to a polymer filament [8]. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most common polymers used in the 3D printing manufacturing. PLA is environmentally friendly, but has relatively poor mechanical properties whereas ABS has good mechanical properties, but emits harmful fumes during processing and exhibits higher shrinkage especially in the open chamber printers [9]. Besides of these limitations, elaborated technology allows to replicate polymer pattern into metal part precisely with all tiny details. Performed roughness investigations confirmed reproducible geometry and high accuracy.

Presented in Fig. 2 roughness profiles both for pattern and casting surface exhibit characteristic regularly folded surface with folds every 0.2 mm reflecting the printed polylactide layers. Similar profiles, slightly disrupted in casting process confirmed the high accuracy of elaborated process and possibility to replace any additive manufactured pattern.

Measured profiles parameters - the mean roughness depth (Rz) and arithmetical mean roughness (Ra) are collected in Table 1. Differences between pattern and casting are very small. Roughness slightly increase after casting process, though clearly lower standard deviation proved that surface topography is more regular. In order to improve surface roughness Daljinder et al. [10] proposed application of the pre-processing and post-processing techniques for FDM pattern e.g. vapor smoothing, chemical treatment. Using this process for manufacturing of bone implants they could control the texture and surface area, which when developed is better integrated with bone via osseointegraion process. Generally surface improvement techniques are being used to meet requirements of particular cast parts. A similar correspondence between the design and the final product was observed in dimensions of casting.

a)



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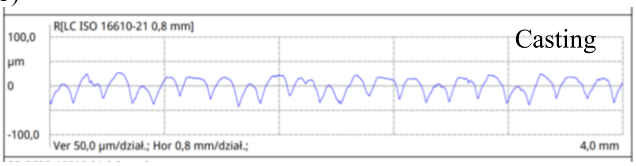


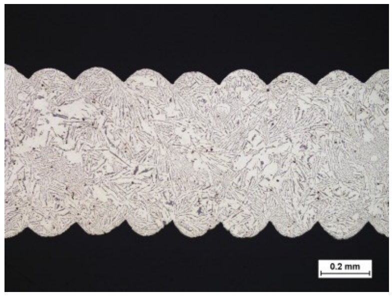
Fig. 2. Surface linear profiles for pattern made by Fused Deposition Modeling (a) and aluminium casting reproduced from polymer pattern (b)

Table 1.
Surface roughness parameters Ra and Rz with calculated standard deviation σ

Material	Ra		Rz	
		σ		σ
3D pattern	12,83	0,88	60,01	1,24
casting	13,02	0,26	60,57	1,16

Microscopic investigations of honeycomb casting show homogeneous microstructure of aluminium alloy, (see Fig.3a). Distribution of silicon crystals in eutectic mixture is regular, with medium length and mild edges. Occasionally gas entrapment and microporosity was observed. Under low pressure (vacuum) metal alloy completely fills intricate mould cavity and solidifies in entire volume with characteristic folded wavy surface character. No visible interaction with plaster mould, surface contamination or extensive alloy oxidization were observed, (see Fig. 3b).

a)



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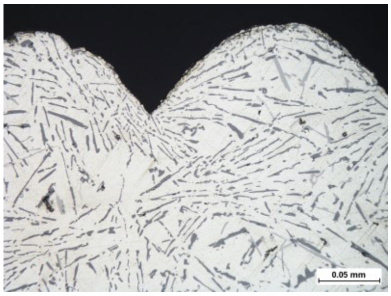


Fig. 3. Microstructure of single wall of aluminium alloy honeycomb element (a), surface of casting with topography after 3D printing pattern (b)

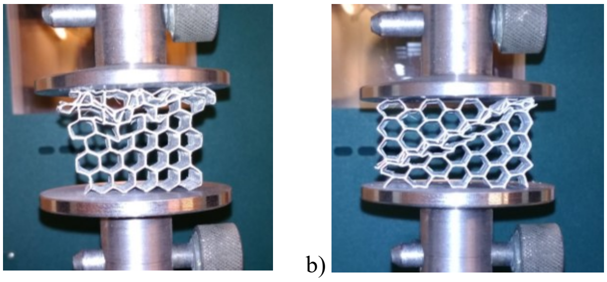
Presented technology can be compared with additive manufacturing methods when laser fuses metal particles, layer by layer, in one process. However drawbacks of those methods are relatively high cost, limitation to short series production and low forming efficiency. Moreover, melting and solidification of small particles, especially chemically active like Mg or Al, result in metallurgical defects as oxide inclusion, porosity and gas entrapment.

Produced castings were subjected to uniaxial quasi-static compression tests with analysis of energy absorption behaviour. Material candidates for automotive applications should convert kinetic energy, e.g. from crush collision, into plastic deformation work of cellular structure. Usually during tests materials undergo local elastic and plastic deformation and finally fracture of cell walls appears. It is demonstrated by plateau region in stress-strain compression diagram. Puga et al. studied the possibility of applying the PLA structure, 3D printed with the use of FDM for the investment casting with Al7Si0.3Mg alloy [11]. Compression strength of such castings was established for various loading directions until the complete collapse of the samples. The maximum value of uniaxial compression strength obtained for as-cast specimens slightly exceeded 15 MPa. As was stated, the periodic stress vs strain dependence is strictly connected with the arrangement of the cellular structure. Each load peak indicates the plastic collapse and finally the fracture of a specific honeycomb row. Among other 3D printing techniques also SLA (Stereolithography) method is being adjusted for investment casting. Xu et al. [12] elaborated the mechanical performance of honeycombs made of Bisphenol A polymer destined to be used as the patterns. Among the strength properties the elastic modulus was determined in three different directions (X, Y, Z see Fig. 5.), taking into account the anisotropic honeycomb structure. Along the Z direction the elastic modulus was 10 times higher than for the X direction. In case of the X direction the failure occurred in sequence for the row after row, while for the Y direction the first ones collapsed the cells located along the diagonal axis of the specimen.

Manufactured samples of cast honeycomb were compressed in two direction (Fig. 4). At position X (the height of the sample was 42 mm) cells started to crush from the top layer whereas at Y (37 mm) position fracture proceed along the plane at 60° angle to the force direction. Measured stress-strain diagram with marked direction of load is shown in Fig. 5. Plateau region with specific folds represents deformation and collapsing of single layer of cells, what needs energy. The energy absorbed per unit volume, when the strain reached 50% can be defined as:

$$E = \int_0^{\varepsilon_{0.5}} \sigma \, d\varepsilon \qquad (1)$$

where σ and ε is respectively compressive stress and strain.



a) b)

Fig. 4. View of compression tests at two orientation of honeycomb 1 (a) and 2 (b) which results are presented in Fig.3

Using formula (1) and measured area under curves absorbed energy per unit volume was 37.6 and 41.2 J/mm^3 respectively for X and Y position. Thus, under similar stress, ca. 1 MPa, honeycomb at position X can absorb ca. 20% more energy.

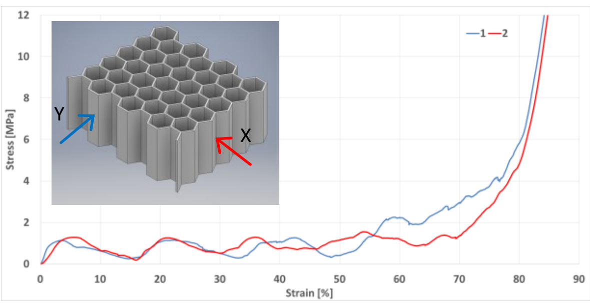


Fig. 5. Stress-strain curves of the cast honeycomb specimens with two orientation of honeycomb channels to load direction

4. Conclusions

In contrast to standard technologies, investment casting combined with 3D printing of pattern allows quickly design and fabricate parts of any shape and complexity. In order to improve and implement necessary modification of casting only software design of pattern can be changed. Promising structural materials can be tailored in dimensions and wall thickness. Honeycombs produced from aluminum alloys exhibits high stiffness, good strength and excellent dimension and surface accuracy. Casting is an exact replica of polymer pattern, with all its details, surface topology and dimensions. Investigated surface roughness of pattern and casting showed that parameters Ra and Rz are very similar. To improve the smoothness of the surface the final metal part pattern can be modified and treated. Castings are characterised by typical for aluminum alloy AC 44200 internal microstructure, with homogeneous fine eutectic. The quasi-static compression tests confirm ability of honeycomb structure for gradual deformation and absorption of energy.

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