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CAST CELLULAR METALS WITH REGULAR AND IRREGULAR STRUCTURES

ULITE KOVINE S PRAVILNO IN NEPRAVILNO CELIČNO STRUKTURO

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An appropriate way to reduce the weight of manufactured parts without adversely affecting their strength is to use porous metallic materials with different internal arrangements of the intentionally created cavities. Porous metallic materials can be made from liquid metal, from powdered metal, metal vapours, or from metal ions. The aim of this research was to verify the possibilities of producing metallic foams by conventional foundry processes, to study the process conditions as well as the physical and mechanical properties of the metal foams produced. The experiments demonstrated the possibility of manufacturing castings with both a regular cellular structure and a solid skin in a single casting operation using different kinds of preform made from commonly used resin-bonded core mixtures. From the perspective of the need to destroy the preforms after the metal's solidification it seems a very interesting prospect to produce preforms from different salts.

Keywords: cellular metals, metal foams, casting

Primerna pot za zmanjšanje mase izdelanih delov, ne da bi občutno vplivali na njihovo trdnost, je uporaba poroznih kovinskih materialov z različno notranjo razporeditvijo namerno povzročenih praznih jamic. Porozne kovinske materiale se lahko izdela iz staljene kovine, kovinskih prahov, kovinskih par ali iz kovinskih ionov. Namen raziskave je bil preveriti možnost izdelave kovinskih pen po navadnem livarskem postopku, študij pogojev procesa, fizikalne in mehanske lastnosti izdelane kovinske pene. Izvršeni poskusi so pokazali možnost izdelave ulitkov z urejeno celično strukturo in čvrsto skorjo z eno livarsko operacijo z uporabo različnih predoblik, izdelanih iz navadnih mešanic za jedra. S stališča potrebne razgradnje predoblike, potem ko se kovina strdi, se zdi konkurenčna izdelava predoblike iz različnih soli.

Ključne besede: celične kovine, kovinske pene, ulivanje

1 INTRODUCTION

Cellular metals and metallic foams are metallic materials containing pores in their structure that are created intentionally. To properly identify the material, according to J. Banhart,[1] one has to distinguish the following: the term *cellular metal* is a general term describing a material in which any kind of gaseous voids are dispersed, in a *porous metal* the pores are usually round and isolated from each other, while the terms foam metal and metal foam are used for a porous metal produced by foaming a melt in which the pores are not interconnected ("structure with closed pores"). In addition, we have the term *metal sponge,* which is used for highly porous materials, in which the pores are connected in a complicated manner and the structure cannot be divided into individual cavities ("structure with open pores"). The term metallic foam is, however, very often used, even in the professional literature, as a general designation of porous materials.

Since the discovery of porous metallic materials numerous methods of production have been developed. According to the state in which the metal is processed the manufacturing processes can be divided into four groups. Porous metallic materials can be made from:[2]

- **liquid metal** (e.g., direct foaming with gas, blowing agents, powder compact melting, casting, spray forming),
- **powdered metal** (e.g., sintering of powders, fibres or hollow spheres, extrusion of polymer/metal mixtures, reaction sintering),
- **metal vapours** (vapour deposition),
- **metal ions** (electrochemical deposition).

Over the past two decades, opportunities for the use of porous metals have increased in many research and industrial applications. Growing interest is related to the specific characteristics of this material. Porous metals represent a new type of materials that fulfil current ecological requirements (particularly in the area of weight reduction) and have unique service properties thanks to a structure with low densities, large specific surfaces, and a useful combination of physical and mechanical properties (absorption of energy, absorption of sound and vibration, thermal insulation, and heat exchange).

Despite the uniqueness of the properties and the wide range of possibilities of use, the number of examples of practical, stable, industrial applications is not large. Nickel foam materials are mass-produced and used as electrodes in rechargeable batteries for portable devices (mobile phones, laptops), while titanium foams are used as implants. At present, the most explored porous metal materials are aluminium foams, which can be documented by the development of prototypes as well as practical applications (small series for AUDI and Lamborghini crash zones).[3] The reasons for the limited use of cellular metals are primarily economic. This is why the current interest (as reflected in a growing number of new published studies and possibilities for industrial applications[4–7]) is focused mainly on the development of technologies enabling the production of foam materials at costs that would allow their widespread use.

The research work carried out at the Department of Metallurgy and Foundry Engineering of the VSB – Technical University aims to study a technique for manufacturing porous metals using the conventional principles of gravity casting in sand moulds. Our intention is to use procedures for liquid-metal processing, enabling the production of complex-shaped castings, not only a simple block of metal foam. The research focuses on two approaches that use the standard foundry technique of casting into disposable sand moulds or permanent metallic moulds with the use of precursors and ceramic prefabricated parts prepared by known methods for core making. These approaches bring low overall costs as well as the advantage of the direct production of parts from complex shapes without any necessary further forming, welding, machining and with use of traditional foundry procedures.

The production of metallic foams using conventional gravity casting into foundry moulds presupposes a more cost-efficient process than other known technologies such as powder metallurgy, metal evaporation and ionization. Cast metallic foams are not yet produced in the Czech Republic.

2 EXPERIMENTAL

The subject of the research was the testing of infiltration techniques for the manufacture of porous metals with both regular and irregular structures. The foundry methods used can be divided into two basic groups:

- two-stage investment casting
- infiltration of liquid metal into the mould cavity filled with different types of filling materials

2.1 Two-stage investment casting

According to this process, a polymer foam, e.g. polyurethane foam, is used as a "lost foam pattern". The pattern is first infiltrated by a slurry of the plaster, to create a plaster "investment". This then undergoes a heat treatment that solidifies the "investment" and burns the polymer foam. Molten metal is poured into the prepared investment, and after the metal's solidification the investment must be removed to leave the internal cavities.

Plaster slurry composition:
100 mass parts of Goldstarpowders MO28 plaster
50 mass parts of water

The material used for the casting was the AlSi10MgMn alloy.

2.2 Infiltration techniques

Infiltration techniques are based on the infiltration of a liquid metal between various filler materials (called a preform or precursor) placed in the mould cavity. Since they do not occupy the entire volume, these precursors form a network of interconnected porosities. The preform must be made of a material that retains its shape during the liquid metal's infiltration (sufficient strength, low abrasion) and can be destroyed after the casting to leave the cavities. The preform must not contain a disconnected island of material so that it can be completely eliminated from the solidified metal.

2.2.1 Use of a precursor as a filler material

Material of precursors that were inserted into the green sand mould cavity:

- granules made of ceramic material with fractions of 8–16 mm and 3–4 mm (**Figure 1**).
- granules made of resin-bonded moulding mixtures (shell-mould, CO_2 resol), fractions 8–16 mm (**Figure 2**).

Apart from the different granulometry, several designs of gating system were used, and the temperature of the filler material was changed (in order to positively affect the castabily of the molten metal).

Figure 1: Ceramic particles with fractions 8–18 mm
Slika 1: Keramični delci zrnatosti 8–18 mm

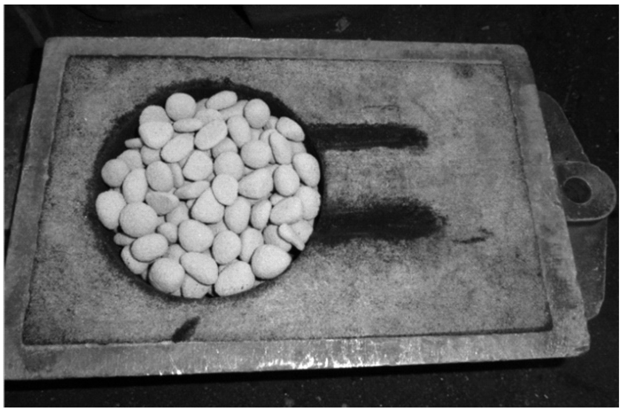

Figure 2: Shell-mould particles inserted into mould cavity
Slika 2: Lupinasti delci, vloženi v livno votlino

The materials used for the casting were the AlSi10MgMn alloy and cast iron with lamellar graphite – in accordance with EN GJL-200.

2.2.2 Use of preform as a filler material

A regular cellular structure can be achieved using different types of preforms that fill the mould cavity. Using a preform like a core not filling the whole mould cavity can make it possible to manufacture a casting with a solid surface layer and an internal porous structure with defined cell dimensions.

For the manufacturing of a sand preform/core it was necessary to prepare a core box. Fused Deposition Modelling technology was used to manufacture the core box. Due to the complex lattice shape of the core, a sectional core box was designed consisting of five parts, which allowed the easy removal of the core.

The materials used for the preform/core manufacturing were:

- CO_2 hardened alkaline phenolic process (the resin is an alkaline phenolic one, containing a linking substance stabilised at a high pH, curing occurs by gassing with carbon dioxide, which dissolves in the water solvent of the resin, so lowering its pH and activating the linking substance.)
- and KCl salt (**Figure 3**).

3 RESULTS AND DISCUSSION

3.1. Two-stage investment casting

The pattern was made of polyurethane foam, the cavities of which was first filled by plaster (100 mass parts of plaster, 50 mass parts of water). The plaster investment was then allowed to dry completely, by subsequently annealing at (100, 500, 640) °C for drying and evaporation of a polyurethane foam. Melting and pouring were made with an INDUTHERM MC 15 device. The equipment enables a combination of vacuum and high pressure to ensure full infiltration. Pouring off takes place using a 90° rotation of the casting unit. The AlSi10MgMn alloy was poured at a temperature 750 °C under a reduced pressure of 1 bar. After pouring, the INDUTHERM MC 15 device automatically switches to an overpressure of 2 bar in order to optimize the mould filling, even for delicate parts. The plaster was removed by dissolving out in water. In the case of a very fine metal foam there are sometimes problems with removing the ceramic without damaging the metal foam. The obtained castings are the exact replicates of the original polymer foam (**Figure 4**) and exhibit the highest porosities (80–97 %). This type of foam provides a very promising application, for example, in the filtration of liquid metals.

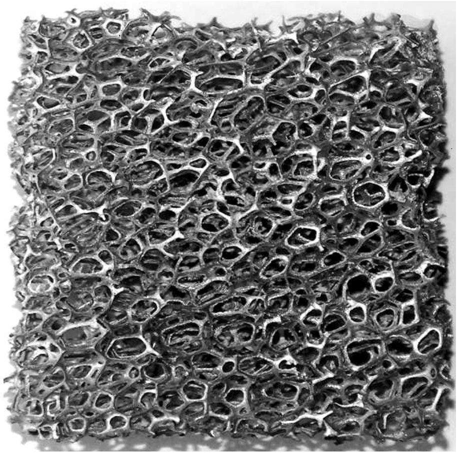

Figure 4: AlSiMg alloy near-net-shape metal foam, porosity 90 %
Slika 4: Drobna mreža kovinske pene iz zlitine AlSiMg s poroznostjo 90 %

Investment casting can also be used to obtain castings with both high porosities and a regular cellular structure.

The pattern was made from extruded polystyrene foam, forming regular structures made from elements bonded layer by layer, as shown in **Figure 5**. The pattern cavities were filled with a plaster slurry (100 mass parts of plaster, 35 mass parts of water). After solidification and sufficient drying of the matrix prepared in this way the pattern/investment was subjected to 8 h of gradual annealing (**Figure 6**) in order to remove the polystyrene

Figure 3: Test samples of KCl salt
Slika 3: Preizkušanci iz soli KCl

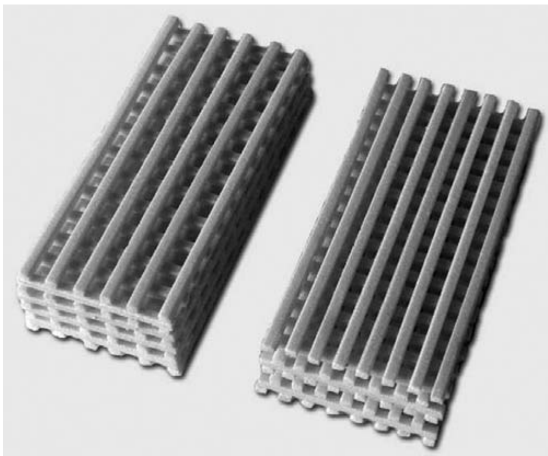

Figure 5: Polymer foam pattern with regular internal structure
Slika 5: Predoblika s pravilno notranjo strukturo iz polimerne pene

Figure 6: Thermal treatment of plaster investment to burn the polymer foam
Slika 6: Toplotna obdelava forme iz mavca, za odstranitev polimerne pene

foam and to achieve sufficient strength as the plaster matrix is subjected to large loads, both thermal and mechanical, during the pouring off.

The plaster pattern was inserted into the cavity of the commonly used green sand mould (bentonite bonded mixture) and then the AlSi10MgMn alloy was poured at a temperature of 750 °C. The plaster was removed by dissolving into a water bath and its residues were removed by a mechanical force in an ultrasonic bath.

The manufacture of castings with a regular cellular structure (**Figure 7**) by investment casting makes it possible to achieve internal cavities (cells) with a precisely defined shape, and thus predicable mechanical properties and reproducible results.[8,9] The main disadvantages of the production process are a high complexity and rather high costs.

3.2. Infiltration techniques

3.2.1 Use of a precursor as a filler material

The performed experiments using different types of precursors[10] proved the feasibility of this method for manufacturing porous metals. The condition of extraction of the precursors after solidification of the metal is an obstacle for the use of ceramic particles because it is generally difficult to remove the ceramic to leave the

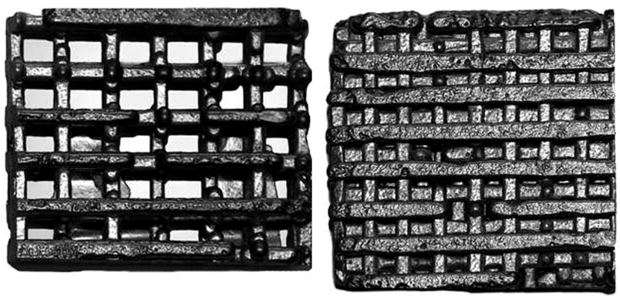

Figure 7: AlSiMg alloy castings with a regular cellular structure, porosities 60–68 %
Slika 7: Ulitek iz zlitine AlSiMg z enakomerno celično strukturo s poroznostjo 60–68 %

Figure 8: Casting made of AlSi10MgMn with remaining precursors
Slika 8: Ulitek, izdelan iz AlSi10MgMn s preostalo predobliko

cavities. More advantageous is the use of granules manufactured from the used resin-bonded core mixtures, which can be easily removed, depending on the pouring temperature and the core mixture collapsibility. In the case of the worse collapsibility the filler material may remain in the casting (**Figure 8**) and its removal would require an additional annealing of the castings (to destroy the resin), which would slightly increase the energy consumption of such production.

The main characteristic of the method using different kinds of precursors as a filler material is the irregular structure and the random distribution of pores throughout the volume of the casting, and therefore the impossibility of achieving reproducible results (**Figure 9**).

3.2.2 Use of a preform as a filler material

The performed experiments have demonstrated the possibility of manufacturing castings with both a regular cellular structure and solid skin in a single casting operation using different kinds of preform made from commonly used resin-bonded core mixtures. The specified resin-core mixture[11] has a sufficient strength and abrasion resistance enabling the handling operation and good collapsibility allows destroying it after solidification.

From the perspective of the necessity to destroy preforms after metal solidification (**Figures 10** and **11**) it seems a good strategy to produce preforms from

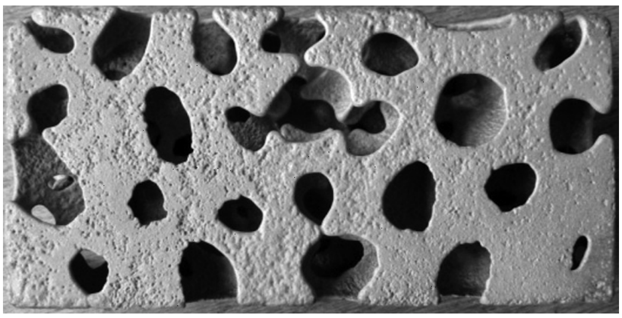

Figure 9: Clean cavities of cast iron EN GJL-200
Slika 9: Očiščene praznine v litem železu EN GJL-200

Figure 10: AlSiMg alloy castings with a regular cellular structure
Slika 10: Ulitki iz zlitine AlSiMg z enakomerno celično zgradbo

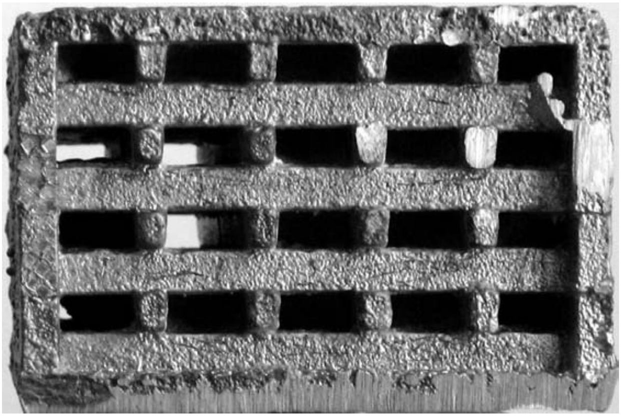

Figure 11: Detail of AlSiMg alloy casting with regular cellular structure
Slika 11: Detajl ulitka iz zlitine AlSiMg z enakomerno celično zgradbo

different salts. The tested salt was 100 % KCl, and the cores were prepared by stamping with a pressing force to 10 t.

The use of the KCl made destroying the preform very easy by dissolving out the water. But industrial implementation would require an extra waste-water treatment circuit, which would make the application more complicated.

4 CONCLUSIONS

Investment casting makes it possible to achieve the highest porosity (97 %) in both types of porous castings. In the case of very fine metal foams, problems may occur with removing the ceramic without the metal foam being damaged. Near-net-shape cast-metal foams provide a promising implementation, e.g., liquid-metal filtration. The manufacturing of castings with a regular cellular structure, using investment casting, makes it possible to achieve internal cavities (cells) with a precisely defined shape, and thus predicable mechanical properties and reproducible results. The main disadvantages of the investment-casting production process are its high complexity and thus rather high production costs. Using different types of precursors as a filler material results in porous castings with open pores in a stochastic arrangement. The main drawback of the method is the irregular structure and random distribution of the pores throughout the volume of the casting. The performed experiments have demonstrated the possibility of manufacturing castings with both a regular cellular structure and a solid skin in a single casting operation using different kinds of the preform made from commonly used resin-bonded core mixtures.

Mastering the production of metallic foams with a defined structure and properties using gravity casting into sand foundry moulds will contribute to an expansion of the assortment produced in foundries by a completely new type of material, which has unique service properties thanks to its structure, and which fulfils the current ecological requirements. The manufacture of foams with the aid of gravity casting in conventional foundry moulds is a cost-advantageous process that can be industrially used in foundries without high investment demands. Metal foams are progressive materials with continuously expanding use. Cast metallic foams are not yet produced in the Czech Republic.

Acknowledgements

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