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METHODS OF ADDITIVE MANUFACTURING USED IN THE TECHNOLOGY OF SKELETON CASTINGS

METODY PRZYROSTOWEGO WYTWARZANIA W TECHNOLOGII ODLEWÓW SZKIELETOWYCH

Rapid development of the methods of additive manufacturing (AM) introduces a number of changes to the design of foundry equipment. AM methods are of particular importance in the development of technology to make small lots of castings or single cast items of complex shapes, such as skeleton castings manufactured also by means of other technologies [1]. AM methods create the possibility of making single-use moulds, cores and wax patterns, as well as patterns made from plastics for repeated use. The development of AM techniques gives theoretically unlimited possibilities in the choice of the designed casting configurations. This fact can be used during the analysis of casting mechanical properties based on the methods of topology optimisation [2], [3], [17], when the said optimisation carried out at the initial stage of design "matches" the shape of parts to the field of stresses or displacements caused by external load and fixing mode. The article discusses the possibilities and advantages that result from combining the new methods of shaping the casting endurance with AM technologies.

Keywords: Additive Manufacturing, Skeleton castings, Topology Optimization

W artykule zaprezentowano możliwości integracji nowoczesnych technologii wykonania oprzyrządowania odlewniczego oraz metod optymalizacji konstrukcji. Systemy przyrostowego wytwarzania (ang. additiv manufacturing, AM) pozwalają na projektowanie bardzo złożonych kształtów konstrukcji, spełniających w znacznie większym stopniu, niż inne metody technologiczne, kryteria kształtowania wytrzymałościowego. Niektóre z szerokiej gamy metod AM, omówione w niniejszym artykule, są szczególnie przydatne w wytwarzaniu form i rdzeni ceramicznych oraz metalowych części oprzyrządowania odlewniczego. Omówiono zastosowanie metod optymalizacji topologicznej w kształtowaniu konstrukcji we wczesnej fazie projektowania, szczególnie w tym przypadku, gdy określone są jedynie założenia dotyczące funkcjonowania podparć i sił działających na obiekt. Przykłady optymalizacji wykonano w oparciu o własny algorytm obliczeniowy, który umożliwia przemieszczanie i eliminowanie masy wewnątrz obszaru projektowego, tak aby przy określonych warunkach brzegowych i sposobie obciążenia, otrzymać najbardziej korzystny stosunek wytrzymałości do masy odlewu. Z reguły w wyniku zastosowania powyższego algorytmu powstają konstrukcje o złożonym kształcie – przestrzenne ramy lub kratownice oraz powierzchnie nie dające się opisać za pomocą prostych jednostek geometrycznych, dla których wykonania właściwe jest stosowanie przyrostowych metod wytwarzania oprzyrządowania odlewniczego.

1. Introduction

The use of AM methods enables, in principle, making any arbitrarily complex shape of the foundry core or mould. The limitations of this method associated with the execution time, the size and accuracy of parts, the size of production batches and types of processed materials are gradually solved, as evidenced by the increasing number of professional equipment and systems of this type. Initially, the AM technique offered the possibility of making wax patterns and patterns from ABS plastics for precision casting, as well as patterns from the laminated layers of paper, resembling with their structure, foundry patterns made from wood. At present, using these systems, it is possible to make sand cores and moulds of relatively large overall dimensions, amounting to as much as 4×2×1 m [4]. It is also possible to make cores with one dimension much larger (theoretically unlimited) than the other dimensions [5]. On the other hand, the technology of metal powder processing extended the use of AM equipment in the field of foundry to include the tooling for dies [6]. The possibility to manufacture parts of any complex shape gives some freedom in shaping the endurance of skeleton castings at an early stage of the design process and more precise matching of the geometry and dimensions of an object to the field of stresses and strains arising from the boundary conditions and loads applied. The initial phase of the design is the step at the beginning of which the shape and size are still unknown, and what is typically required is their choice such that will make the whole construction more lightweight and durable. The question of the mechanical strength is in this case reduced to searching for the optimum weight distribution in three-dimensional space. The problem can be solved with the, so called, topology optimisation which, due to the specific nature of the method itself, usually results in the creation of thin-walled openwork

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TABLE 1

Selected parameters of printing and printers for foundry applications [4-5], [9-10]

Manufacturing Company	Type of printer	Pattern dimensions	Print speed	Thickness of layer	Material and binder
ExOne	S-Max	1800×1000×700 mm	165 000 cm^3/s	0.28 – 0.50 mm	Silica sand +furan resin
ExOne	S-Print	800×800×400 mm	86000 cm^3/s	0.28-0.38 mm	Silica sand + silicate binder
Voxeljet	VX 4000	4000×2000×1000 mm	75 s/one layer		Silica sand + inorganic binder
Voxeljet	VX 800	800×500 mm	Continuous printing	300μm	Silica sand + inorganic binder
Solidscape	3Z MAX	152×152×101 mm			Wax

designs. The following is a brief overview of the AM methods such as 3D printing, powder layers fusion and extrusion, most of which are also applicable in the manufacture of foundry equipment. Selected features of topology optimisation were also briefly discussed on the example of an arbitrary bar structure. Another presented example referred to the application of wax patterns in the manufacture of test skeleton castings.

2. The method of 3D printing

The first commercial device using the 3D printing technology was ModelMaker presented in 1994. Printing consisted in applying to the substrate through a nozzle, successive layers of wax (preheated to its melting temperature) [7]. A characteristic feature of this method was the formation of an entire pattern with the supports, if any, from the material fed through the head in the form of drops, in a way similar to the inkjet printers. The most commonly used are two methods of creating and dispensing the drops from the nozzle: a continuous stream (CS) and drop-on-demand (DOD) [8]. The difference lies in the configuration of the stream leaving the nozzle. In the CS method, the stream leaving the nozzle maintains its continuity for a lapse of time and then isolated drops are detached, while in the DOD method, only single drops are leaving the nozzle. The kinetic energy with which the droplet leaves the nozzle must be large enough to let this drop travel a specific path with a predetermined speed and create a new surface after hitting the substrate. This method is used in precision casting to produce wax patterns.

On the other hand, printing consisting in feeding through a printer the sole binder on the previously applied powder substrate was developed in 1990 at the Massachusetts Institute of Technology. This process was named 3D Printing (3DP). By means of this technique it is possible to make patterns from a wide range of materials such as polymers, metals and ceramics. In this embodiment of the printing method, only a small quantity of the substance is supplied through the nozzles. Drops of binder (80 μm diameter) form together with powder particles a spherical agglomerate within which the particles get combined with each other and with the previously formed layer. Because the head may comprise a series of nozzles, the 3DP process can be classified as linear. The process yield can be increased by printing simultaneously several different patterns. Using this printing variety, both moulds and cores can be made. Table 1 lists some parameters of the printers dispensing wax pattern material and the sole binder.

3. The method of powder layers fusion

The process of powder layers fusion with its best known variation, which is selective laser sintering (SLS), comprises thermally connecting thin layers of powder applied onto the pattern surface using a roller distribution device. When a layer of powder is applied and heated up to the required temperature, focussed laser beam is directed onto it and moves along the programmed path. In the SLS process, combining of powder grains is usually defined by words such as “sintering” or “melting”, but the issue is more complex, and both terms do not fully exhaust the description of the phenomena that occur then. There are four different mechanisms connecting the grains, namely the solid-state sintering, combining by chemical reactions, liquid phase sintering, and consolidation by complete melting of the powder [11]. Variations of powder layers consolidation method are associated with the type of material being processed, wherein the particles (grains) can be divided in terms of their structure into individual particles, particles forming a composite, coated particles, and particles with alloy microstructure without differentiating between the solid phase and binder. In the foundry industry, these methods have been used to make moulds and cores from resin-coated sands, and in repair, regeneration and fabrication of metal tooling parts such as die inserts. These methods are used in the devices made by EOS in Germany. In 1995, an EOSINT M 250 system was created to make sand moulds for casting of metal alloys, and the latest version of this device is EOSINT S 750 with two CO_2 lasers with a capacity of 2×100 W. In 1998, an EOSINT M250 Xtendet was launched, in which a Direct Metal Laser Sintering (DMLS) was used for sintering of metal powders in a liquid state. In the first versions of this unit, a special mixture containing powders of bronze and nickel from Electrolux Rapid Prototyping was processed. Currently, the range of materials used has been greatly expanded. The latest model is EOSINT M280 device provided with Yb fibre laser with a power of 200, 400 or 1000 W, by means of which from the EOS MS1 Maraging Steel one can make tooling for the pressure die casting of aluminium alloys. A particular advantage of the method is the possibility of making any arbitrarily complex system of cooling channels close to the surface of the insert.

TABLE 2

Selected parameters of equipment used for powder layers consolidation in foundry applications [12-13]

Manufacturing Company	Type of equipment	Pattern dimensions	Scanning speed	Minimal wall thickness	Thickness of layer	Material
EOS	EOSINT S 750	720×380×380 mm	2500 cm^3/h 3 m/s		0.2 mm	Silica sand coated with phenolic resin
EOS	EOSINT M 280	228×228×304 mm	Do 7 m/s	0.3 do 0.4 mm	20 do 40 μm	EOS MS1 MaragingSteel

4. Systems based on extrusion

In this embodiment of AM technology, the material in the pressurised reservoir is extruded through the nozzles. If the pressure does not change, the material flows through the nozzle at a constant speed and the cross-section of the stream remains constant. The material extruded through the nozzles must be in a semi-solid state. After applying a layer of material and shaping this layer to the required geometry, the material should pass into the solid state. Additionally, the superimposed material must be connected with the previously applied layer to form an AM pattern. When a layer is applied, the heads should move up or move the pattern down to apply the next layer of the pattern. Using FDM devices, patterns can be made from ABS developed for the needs of this technology, used in investment casting like wax patterns. The difference between these materials is in the method of removing the pattern from the mould cavity – the wax is melted out, while the ABS resin is burnt out leaving a very small amount of ash (0.021% of the pattern volume), which is removed from the mould cavity. The mould should be provided with vents, which accelerate the ABS burning out process [14]. A company that specialises in the design of devices based on the FDM technology is Stratasys. FORTUS series devices are characterised by very high precision of the pattern-making operation. Using the largest unit in this series, i.e. FORTUS – 900, it is possible to make a pattern with overall dimensions of 914×610×914 mm; it also offers the highest accuracy of performance – the thickness of a single layer can be only 0.076 mm [15].

5. Skeleton structure as a result of topology optimisation

Topology optimisation process is carried out in the, so-called. design space, and its effect is the removal of material from some of the space sub-areas in which the magnitude of the tension caused by the load remains relatively small. The space design is mostly a lump of simple shapes (rectangular prism, cylinder, sleeve, prism), the corresponding edges of which are supported and loaded in line with the design guidelines. The material can not be removed from the sites that are responsible for the functionality of the structure. The optimisation process is evolutionary, because the boundary problem is solved repeatedly, and the mass in the design space moves to those areas where the effort of material assumes the highest values. If appropriately dense breakdown of the area with finite elements has been adopted, the solution, which consists in determining the optimal topology of the body with a minimum sensitivity, is obtained relatively quickly, after a small number of iterations. This solution is equivalent to obtaining such a distribution of material in the design space that some areas will comprise the material with a density ρ and initial module E_0, while in other areas this material will be absent. Figure 1 shows the results of optimisation of a supported arch structure loaded uniformly from the top. The computer calculations were carried out based on, the Finite Element Method, and authors subroutines optimization algorithm elimination of elements [17]. The loss of "mass" in the structure following the successive steps of calculation is well visible. After the fifteenth iteration, the allowable stress values are exceeded and the optimisation process is considered complete. The space design was chosen in such a way that its shape was as close as possible to that which was defined by the initial design intent.

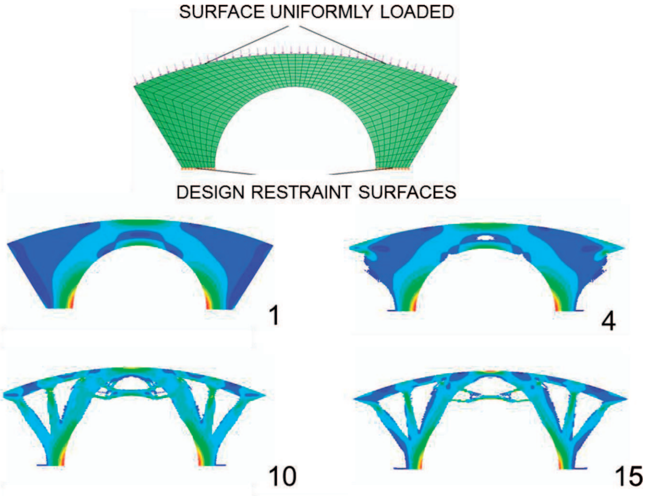

Fig. 1. The design area and the results of optimisation after 4, 10 and 15 iterations, red colour denotes places where the reduced HMH stress assumes the highest value, blue – the lowest [17]

6. AM pattern for a skeleton casting

According to M. F. Ashby and LJ. Gibson [16], the spatial structures are defined as a network of interconnected beams or plates that form the edges and surfaces of the base cell. Typical example of this type of connections is the structure of honeycomb, wherein the plates are joined to each other with the edges to form a unit cell of the shape of a polygon, and a lattice-type structure made of beams combined at the nodes – Figure 2.

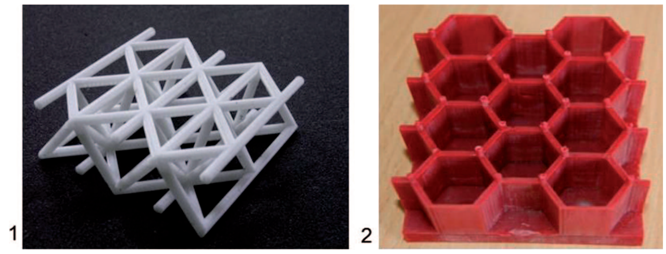

Fig. 2. AM models of spatial cellular structures; 1 – ABS, 2 – Wax [18],[19]

The precision casting method to obtain an ordered structure of the cell uses patterns made by the AM method. The patterns made of wax or ABS plastics (acrylonitrile – butadiene – styrene resin) by additive methods may have substantially any shape. Certain restrictions apply to the casting wall thickness and are related to the fluidity of alloy and access to the space, from which the moulding material has to be removed. One can use lost patterns heated and burnt out before pouring of mould or, using the pre-made AM pattern, construct silicone matrices, in which dozen wax patterns can be made. Due to the complex shape of the structure, alloys with good castability such as Al-Si, Cu-Be and superalloys are usually used. The advantage of this method is the possibility of making castings of the spatial structures of the shape more complex than the shape of the structures that are usually obtained by the methods of plastic forming and assembly (sandwich type structures). Thus the shape of skeleton casting can be designed in such a way that the external force generates minimum stresses, while the mass of the casting has been reduced – Figure 3.

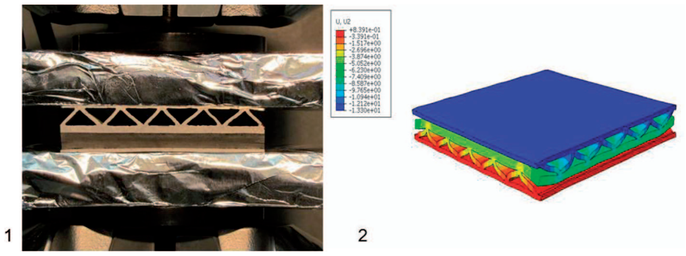

Fig. 3. Skeleton casting strength test, 1 – compression test, small deformation of the cell walls is visible, 2 – stress and determined by FEM model deformation visible just before the destruction [18]

7. Summary

The development of additive methods of manufacture caused that, in addition to the support of design work, AM patterns can be used in various other ways, also as a final product or structure. In the foundry industry, these methods can be used to produce ceramic moulds and cores, and for pressure die casting tooling. Particularly useful in this case are the techniques of 3D printing, FDM method, and some varieties of powder layers consolidation. They eliminate, to a large extent, the constraints resulting from the relationship between the casting shape complexity and design manufacturability. This fact is useful when the strength of a structure is developed at an early stage of the design work, when only the initial assumptions related to the purpose, functionality and overall dimensions of the casting are known. The use of topology optimisation methods allows movement and elimination of mass within the design area to obtain at certain boundary conditions and loading process the most favourable casting strength-to-weight ratio. In general, as a result of the application of the above algorithm, structures of complex shape are created, such as the spatial frames or trusses and surfaces which can not be described using simple geometric entities. A simple case of the structure with optimised strength-to-weight ratio is the, so called, skeleton casting. This is usually a "sandwich" type structure transferring only the forces causing the deformation of two parallel planes. When the constraints that are inherent in the above specified design concept are eliminated, a spatial shaped skeleton structure is obtained, which will transfer in an optimum manner the loads exerted onto it, acting in any arbitrary direction.

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