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Novel concepts for the design of moulds and equipment for expanded polymer bead foams

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Abstract

Metal additive manufacturing is proposed as route for the manufacturing of moulds for expanded polymer parts. The traditional tools used in steam-chest moulding technologies can be replaced by lighter moulds accurately designed and produced by the laser-powder bed fusion technology, with significantly reduced thermal capacity and optimized ability to homogeneously deliver the steam throughout the part volume.

The general design approach is described and the performance of the innovative tested solution is presented by the discussion of a case study. The experimental tests carried out on the moulds and moulding equipment prototypes showed remarkable reduction in cycle times and energy consumption when compared to a traditional steam-chest moulding used to print the same product.

Keywords: expanded polymers, additive manufacturing, laser powder bed fusion, steam-chest moulding, mould design

1. Introduction

Polymer foams represent an important class of materials where the polymer matrix contains a large amount of pores so as to reduce density and impart other interesting properties such as low thermal conductivity, improved acoustic insulation and energy absorption capacity. The combination of such properties makes polymer foams very attractive for a wide range of applications including packaging, sport and safety equipment, crash absorbers and bumpers, insulating panels, car interiors and other parts in the transportation, military and building sectors [1,2].

A wide spectrum of processing techniques has been developed for the foaming and shaping of a range of polymers, typically polypropylene, polystyrene and polyurethane. One of the most popular shaping technology is bead foaming by steam-chest moulding. It makes use of a feedstock of expandable or already expanded foamed beads that are injected into a mould by air pressure and welded together under the action of pressure and temperature. Consolidation of the beads into a defined shape takes place by a sort of sintering whereby a flow of water steam under pressure (usually at temperature up to 150°C, and pressure up to 8 bar) melts or softens the surface of the beads, promoting the interdiffusion of polymer chains and forming physical links with controlled amount of inter-particle voids [2,3].

The achievement of the best mechanical and functional properties in the expanded polymer (EP) parts is therefore related to a strict control of the processing environment supplied to the beads in the mould, to ensure a temperature distribution as uniform as possible, hence a stable quality of the sintering process throughout the volume of the part. The cooling stage is also important since it affects the dimensional stability. If the part is ejected too early, warpage or uncontrolled expansion may occur leading to shape distortions [2].

The moulds for steam-chest moulding of EP are traditionally built by massive aluminium-alloy castings. They are subjected to significant thermal fluctuations during processing that promote consistent energy wastes and environmental concerns. The mould and chest walls are heated by the steam flow before it is injected through nozzles in the chamber filled with the beads. On cooling, a flow of water (or water sprays) replaces the steam in contact with the mould in order to speed up the cooling stage of the part, allowing its safe ejection. Process-cycle times are therefore ruled by the rate at which the whole system can follow the desired thermal history, while the energy requirement is set by its overall heat capacity.

These factors are currently driving the innovation in the field of steam-chest moulding technologies, aimed at increasing energy savings, reducing moulding times and making the process more environmental friendly. Patents have been filed claiming the improvement of the steam chamber insulation by using low conductive metals or suitable coatings [4] and the design of moulds without the conventional steam chest, which is replaced by injectors and nozzles for steam and cooling media respectively, delivered on the mould surface through a confined volume that acts as the media distributor [5]. Microwaves have also been proposed as the heating medium instead of steam [6]. From open literature it is known that Hossieny et al. studied the effect of additional hot air as a secondary medium for heat transport, demonstrating a shortening of the moulding times and a reduction of energy consumption [3]. Recently, approaches based on metal Additive Manufacturing (AM) have been proposed to improve mould efficiency [7,8]. AM offers a wider design freedom and the ability of fabricating shapes that are impossible for conventional manufacturing technologies. Accordingly, Schütz and co-authors designed a thin-walled mould that also incorporates a conformal steam chamber stiffened by an internal 3D lattice. A prototype was printed by a Laser-powder bed fusion system and successfully tested [7].

The present paper describes new design concepts based on AM for the manufacturing of tools and equipment for the bead foaming technology. Specifically, innovative moulds for the processing of EP have been developed exploiting these concepts and tested on real products to evaluate their performance in light of a more sustainable and energy efficient design approach.

2. Opportunities offered by AM for expanded polymer moulding

AM technologies allows building three-dimensional (3D) near net-shape complex objects by progressively adding thin layers of materials guided by a digital model. AM processes were initially proposed for producing prototypes, but in few decades their use mainly moved to the fabrication of functional and structural parts for service in industrial, transportation and medical applications. Among the existing AM processing methods, Laser-Powder Bed Fusion (L-PBF) is recognized as the most appropriate technique for the manufacturing of small- to medium-size parts with good accuracy even for small geometrical details [9,10]. L-PBF is based on the local melting of a metal powder bed by a high-power density laser beam. Gas-atomized pre-alloyed powders with round shape, smooth surface, and size distribution that usually spans from 20 to 60 um are commonly used in L-PBF. Their high packing efficiency and their good flowability allows the powder to be easily and homogeneously distributed in flat and thin layers (30-50 um).

L-PBF allows creating small geometrical features with a resolution of the order about 0,1 mm, already in the printed parts. These features are achievable without additional costs and irrespective of their number, since they are designed and directly included in the CAD file. Taking advantage of this opportunity, the tooling industry has been very active in recent years on the development of innovative tools, especially when considering the opportunity of implementing conformal cooling channels in the interior of tools and dies [11-14].

Concerning the moulds for the bead foaming technology, AM allows adopting new design concepts that revealed to be successful for productivity and quality of the products. Some general ideas will be presented in the following paragraphs whereas a detailed case-study of a mould will be introduced in the next section.

By L-PBF, a series of uniformly distributed small holes can be readily obtained on the mould surface, to replace the steam nozzles usually inserted in moulds, whose prints are well visible in conventional steam-chest moulded parts, as depicted in figure 1. Additionally to the aesthetical improvement of the part surface, a more uniform distribution of the steam during bead sintering can be achieved, which brings significant advantages to product quality, providing the desired properties throughout the part volume.

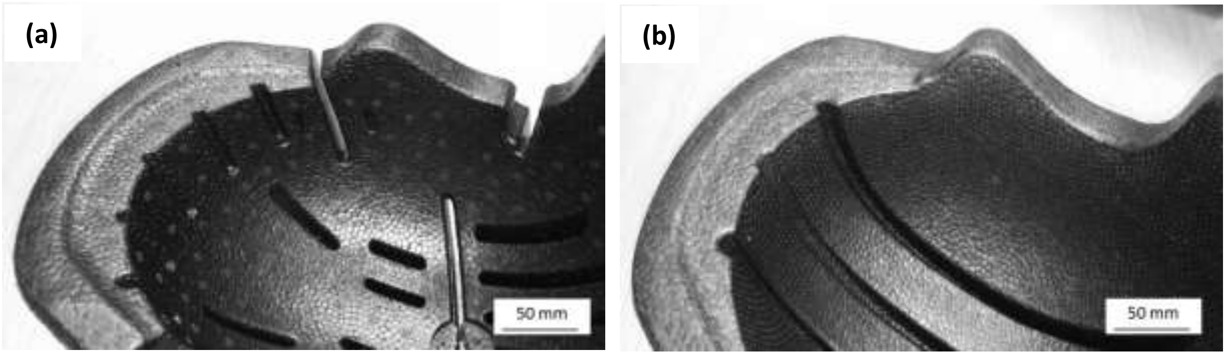


Figure 1. Evidence of the steam-nozzle prints on surface of a part produced by traditional steam-chest moulding (a); part surface moulded by a tool produced via L-PBF, with diffused holes (0,2 mm in diameter) for steam injection.

AM additionally lends itself to the flexible fabrication of material volumes with complex internal architectures such as random or ordered (micro)porous walls and 3D periodic lattice structures [15-18]. Microporous mould walls would represent a further step forward for the homogeneous delivery of the steam to the polymer beads to be sintered. Moreover, the potential ability of tailoring the fraction of porosity, can rule the amount of steam (hence heat) locally transferred to the beads, allowing the optimal thermal cycles to be induced on distinct volumes and to achieve the desired properties of the expanded foam. Figure 2 depicts examples of an ordered microporous materials produced by L-PBF. The hatch distance of the porous architecture can be set independently along the different directions in order to exactly meet the requirements dictated by the optimal processing parameters.

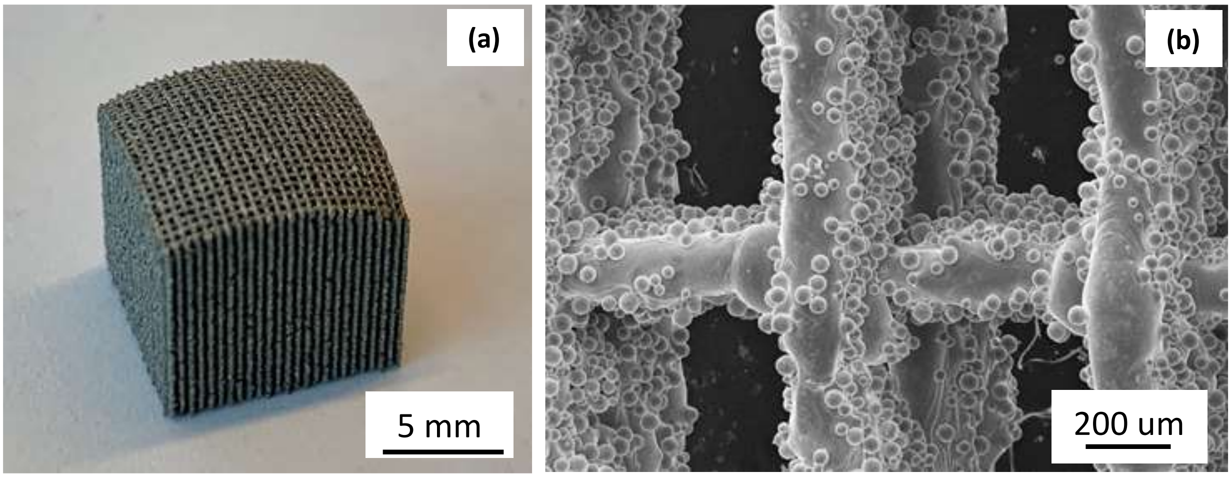


Figure 2. Ordered microporous Ti-6Al-4V alloy sample produced by L-PBF; (a) general view of a printed sample block, (b) high magnification SEM image of the micro-lattice.

AM has been widely exploited for the fabrication of macroscopic 3D periodic lattice structures formed by a truss-like architecture of interconnected struts and nodes occupying specific volumes. Macroscopic 3D lattices have a variety of advantages including a high stiffness-to-weight ratio [17,19], controllable and tunable mechanical properties [16,20,21], excellent energy absorption [19,22] and heat exchange characteristics [23-25]. In light of this opportunity, the wide steam chamber adopted in conventional steam-chest moulds can be replaced by a thin sandwich structure composed of two thin sheets and an internal structural 3D lattice. Figure 3 describes an application example where the lattice structure has been designed in order to sustain the working loads during moulding, but also to improve the thermal performance during the processing cycles.

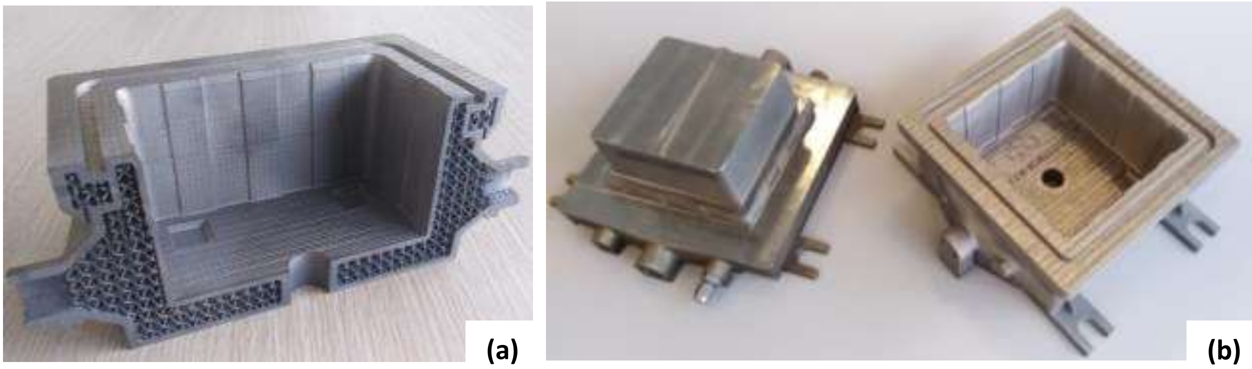


Figure 3. The use of a structural 3D lattice in the steam chamber of a mould. View of a sectioned prototype of a mould (a); the set of moulds for the bead foaming of a food container (b).

Finally, consideration should be given to the proper selection of the materials to be used for moulds designed according to the described innovative concepts. Up to now, aluminium cast alloys have been considered as the reference materials for traditional steam-chest moulds due to their good castability and the need of increasing the thermal diffusivity and reducing the heat capacity of the traditional massive tools. However, the described trend toward the use of much thinner mould walls (of the order of 1-2 mm) and the ability of rapidly delivering the heat to the polymer beads through the diffused pores, would bias in favour of different material options, featuring lower thermal conductivity and heat capacity, so as to reduce as much as possible the amount of heat transferred to the moulds during the faster cycles, hence saving energy and reducing the required amount of cooling fluids before starting the following cycle. In table 1 reference thermal properties for a selection of pure metals and alloys are summarized. It can be inferred that possible alternatives such as the 316 stainless steel, commercially pure Ti or the more popular Ti-6Al-4V alloy could be favourably considered for the current innovative application.

Material	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	CTE ($10^{-6} \cdot K^{-1}$)	Specific heat ($J \cdot Kg^{-1} \cdot K^{-1}$)	Density ($Kg \cdot dm^{-3}$)
pure Al (1050 grade)	231	23,6	900	2,71
pure Cu (10100 grade)	391	17,3	385	8,94
pure Fe (1008 grade)	65	11,6	481	7,87
pure Ti (grade 1)	16	8,6	544	4,51
316 stainless steel	16,2	15,9	500	8,03
Ti6Al4V alloy	6,7	8,6	526	4,48

Table 1. Physical properties of interest for a selection of materials and alloys for the design of moulds for expanded beads by AM [data from 26,27].

3. Case study: helmet body moulded with expanded polypropylene

The design of moulds for expanded polymers to be manufactured by AM implies the matching of a combination of requirements set by the functional needs of the final product and by the moulding process, also considering the constraints given by the 3D manufacturing route.

A very large number of helmet bodies are worldwide printed with expanded polypropylene (EPP) to satisfy the demand of equipment for sport (cycling, climbing), transportation safety and childcare. Their geometry and size generally imply fairly large and complex moulds while their safety requirements ask for a full control of the quality of the moulded material in any region of the helmet, to guarantee strength and lightweight. Considering the mass production characteristics, cycle times and expected mould life, together with energy wastes and environmental sustainability become factors of primary importance.

The new concept of mould design here proposed is based on the adoption of a sandwich structure composed of two thin sheets and an internal 3D lattice. The skin exposed to the EPP beads is required to be as thin as possible to fasten the moulding cycles and to save energy. The chamber volume contained within the two skin surfaces of the sandwich (the conveying chamber) should also be limited to reduce the amount of steam and water required for the moulding cycles. The features of the 3D lattice must be defined considering a compromise between the need to reduce the mass subjected to the thermal cycles and the strength against the structural loads induced by the moulding process. A network of small holes is created throughout the skin in contact to the beads, to homogeneously deliver the water steam, replacing the discrete nozzles adopted in conventional moulds.

The shape definition is finally bound to rules set by the AM fabrication (see for instance ref. [28]). Downskin surfaces with respect to building direction and overhangs should be limited to reduce the amount of support structures (to be removed after the print), orientation of the most functional surfaces should be optimized to improve roughness quality, the lattice structure is finally selected in its geometry in order to limit the manufacturing time and assure integrity of the moulds during their lifetime.

Moreover, it is considered that the lattice structure within the conveying chamber affects the fluid flow pattern and could impair the homogeneous heat flow delivered to the polymer beads. To this purpose, a computational fluid dynamics (CFD) analysis, developed with ANSYS software, has been carried out to compare different lattice geometries and to evaluate their impact on the flow of the fluids (water and steam) in the conveying chamber. The approach adopted consisted in changing locally the size and the position of the lattice in order to achieve acceptable flow conditions, also considering the structural function required for the lattice.

An output of analyses performed is reported in figure 4 which shows the trend of the fluid flow into the conveying chamber with and without the presence of the lattice structure. The specific case reports the values of the velocity streamlines of an air flow in the conveying chamber of the mould when setting an inlet velocity of 0,5 m/s.

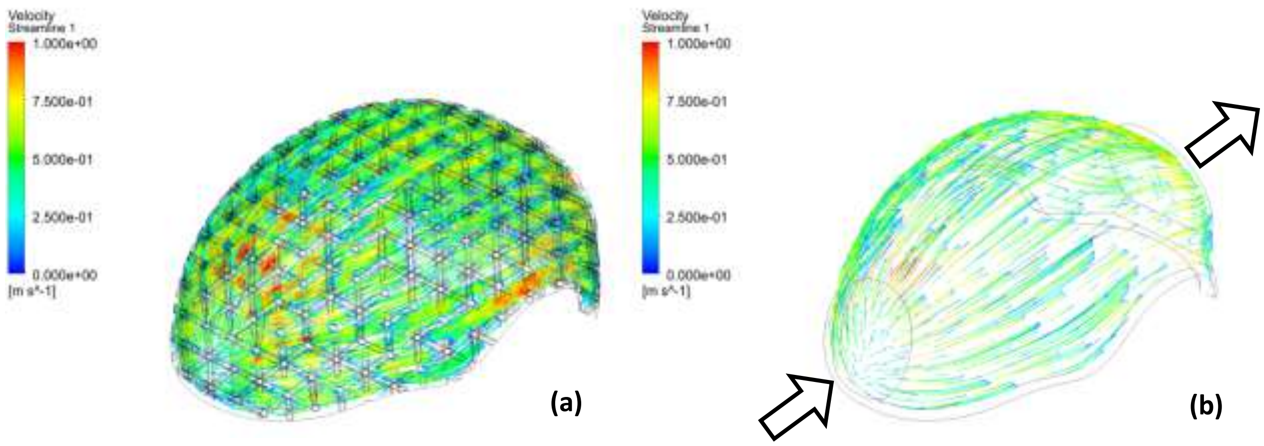
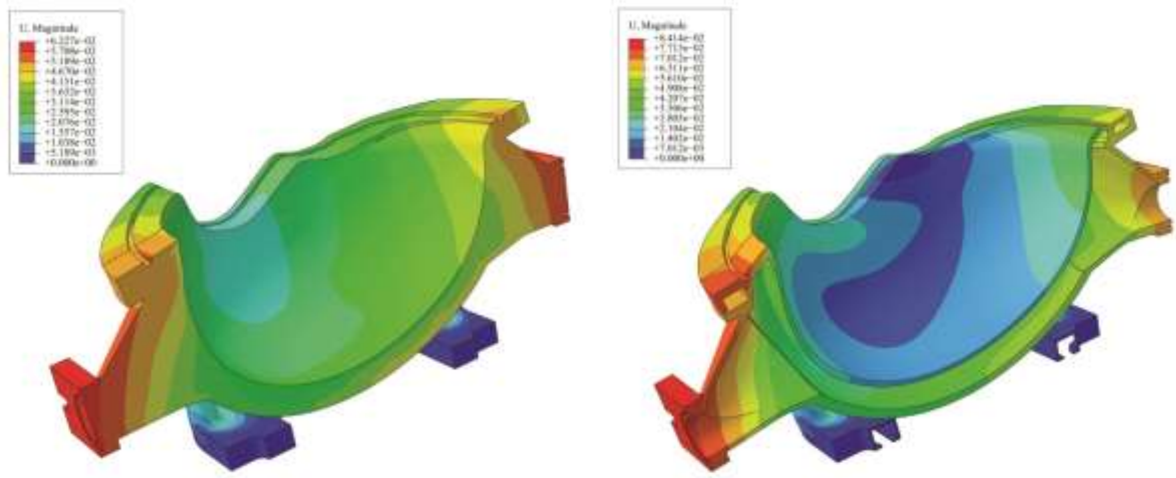


Figure 4. CFD simulation of the fluid flow into the conveying chamber of the female mould. Flow pattern with chamber filled with the 3D lattice (a) and with empty chamber (b). Inlet of fluids is on front surface of the helmet, outlet is on the opposite rear surface (see arrows in figure b).

As already stated, the lattice structure also has to be designed to sustain the moulding loads at the proper processing temperature. The analyses have been conducted using a finite element model (FEM) by the ABAQUS software, considering two simplified geometric models of the mould and applying on its surface a pressure of 5 bar, corresponding to the internal pressure applied in the main chamber of the mould during the process. In a first case the lattice structure was computed by means of an equivalent material featuring the same macroscopic properties of the lattice, as defined by the CFD analysis (see figure 5a). The adoption of an equivalent material to simulate the presence of the 3D lattice structure into the conveying chamber allowed reducing significantly the complexity of the model and the computational time. A second situation was then considered, where the 3D lattice was totally omitted in order to derive information about the contribution of the lattice to the mould stiffness (see figure 5b). The information drawn by the FEM and the CFD models allowed a more robust design of the moulds while keeping the lightweight property as the main target.



(a) **(b)**

Figure 5. FEM simulations of the deformed female mould when subjected to water steam pressure at the process working temperature (the legend refers to the total deformation, in mm). Model with an equivalent material simulating the mechanical behaviour of the lattice (a) and without lattice structure in the conveying chamber (b).

Figure 6 shows an interrupted print of the designed mould made in 316L stainless steel. The complex lattice occupying the inner volume of the conveying chamber is clearly visible on the exposed section. It is to recall that the building platform of 280 x 280 mm was almost fully occupied by the printed part. Despite the optimized orientation of the part, extensive use of supports was needed to sustain the correct generation of the surfaces to be printed in the upcoming layers.

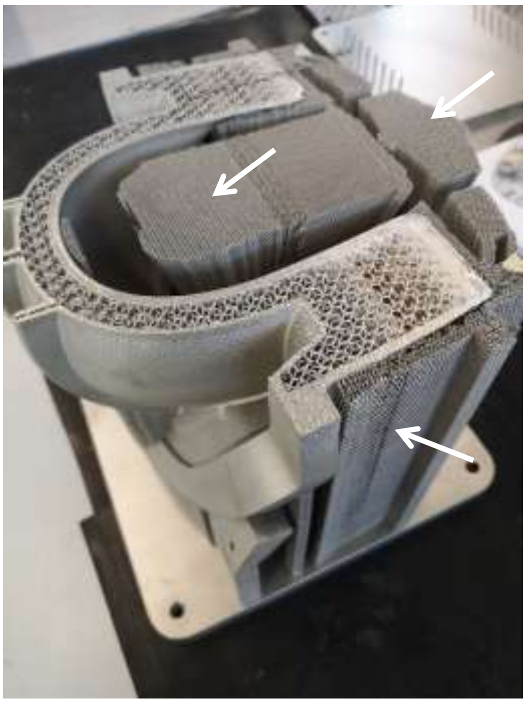


Figure 6. View of an interrupted print made by L-PBF for one of the designed moulds. The support structures are shown by arrows.

Based on the new architecture of the proposed moulds, a more efficient moulding system could be designed as well, to fully exploit energy savings and reduction of cycle times. In figure 7 a general view of the innovative system and of the finished moulds used to produce the EPP helmets are depicted.

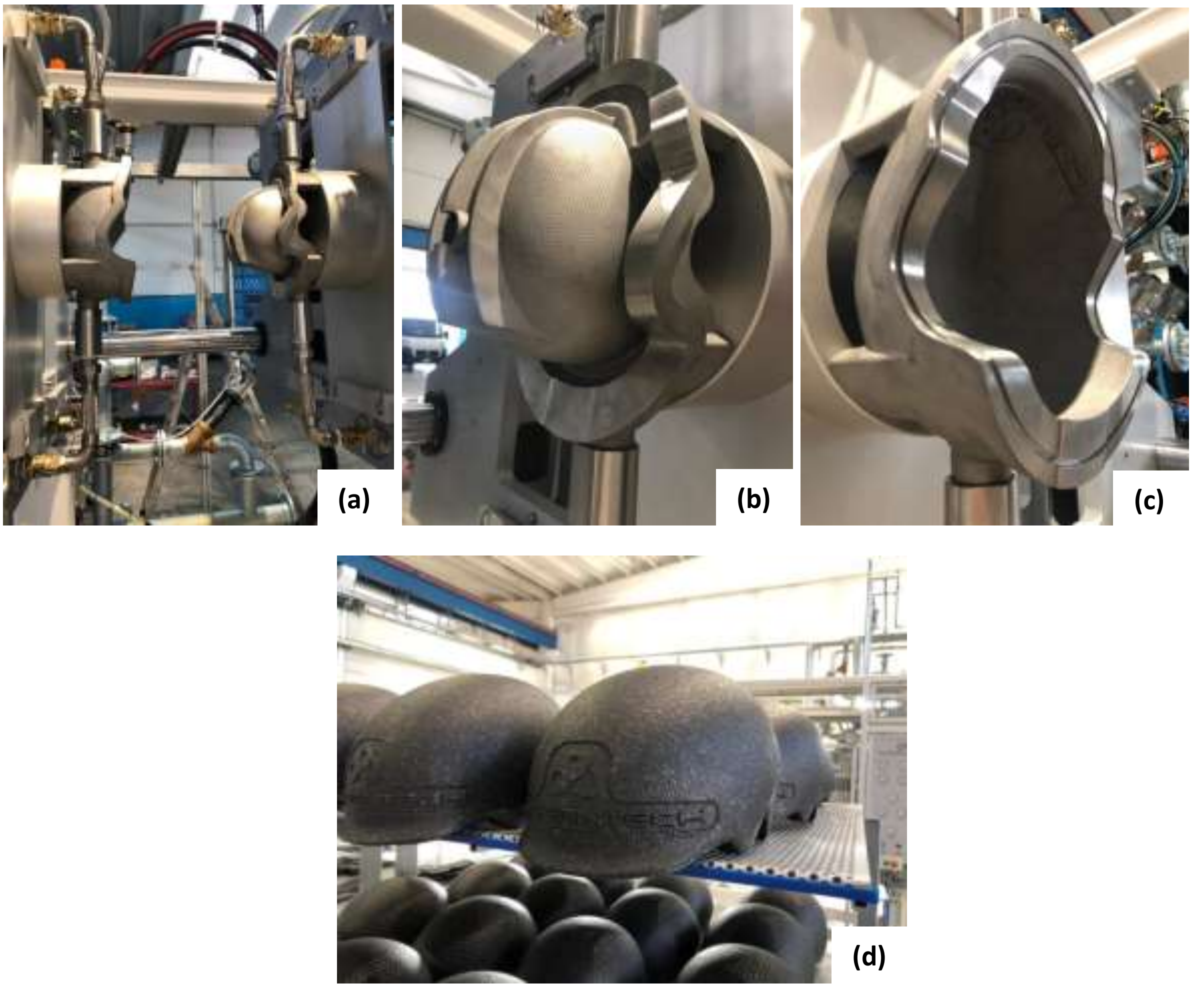


Figure 7. Views of the specifically designed moulding apparatus (a), of the finished moulds for the production of EPP helmets (b and c) and samples of the moulded parts (d).

The newly designed moulding press relies on electric drives, replacing the hydraulic ones, that can actuate the opening and closure of the moulds at a faster rate. However, the main contribution to reduction of processing times comes from the dramatic contraction of some of the processing steps, as summarized in figure 8.

In broad terms it can be stated that the moulding process of the EP beads can be split into a preliminary phase concerned with filling of the mould with the bead feedstock, followed by the cooking and the cooling phases before the extraction of the formed part. In the comparison presented in figure 8 the filing and extraction phases were actually not considered since they are substantially identical in both process versions, even though the electric drives would allow a further reduction of the mould opening and closing times to be achieved.

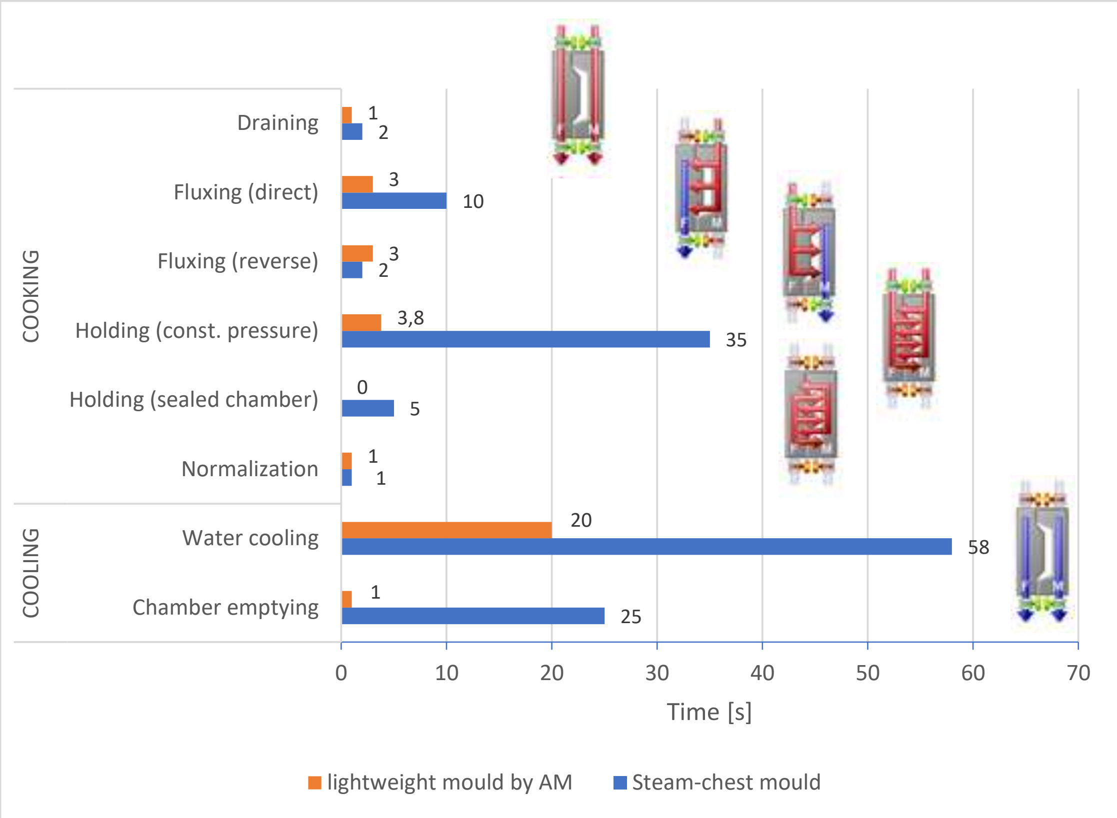


Figure 8. Time comparison of the main moulding steps for EPP processing according to the traditional and innovative approaches.

Cooking refers to the phase where the steam is injected into the moulds and interacts with the beads, promoting their sintering. The system controls the steps of (i) draining and (ii) fluxing the steam (in two different directions: direct and revers flow) to heat the mould and the feedstock, and (iii) maintaining the high-pressure hot environment by dynamically holding (autoclave) the pressure and then sealing the chamber to consolidate the part. A so-called normalization step follows (iv) which brings the mould environment back to the atmospheric pressure.

In the following cooling phase, water is circulated into channels fixed inside the mould chest (or directly in the conveying chamber in the new design) so as cool it down to about 40-50°C. Water is then removed from the circuit to prepare the mould for the following cycle. It is to remark that this last step is not required for the new mould architecture since the conveying chamber has a very limited volume.

The data given in figure 8 highlight that the main difference when using massive moulds (traditional process) rather than the innovative AM light moulds (new design) greatly depends on the amount of volume that has to be filled by the heating/cooling media and on the solid mass that is actually subjected to the temperature changes. In summary, when comparing the productivity of the above described new solution to the traditional steam-chest moulding technology, for the same type of printed helmet, a reduction of cycle time of 75% was achieved while energy saving could be quantified to about 80%.

Finally, it is worth considering that the adoption of slightly different moulding steps also implied the definition of different optimized process parameters. The quality of the EP products produced by the innovative moulding process revealed to be similar to that achieved by the conventional processing route. The precise quantification of the properties was out of the scope of the current research and will be presented in a future work.

4. Conclusions

A novel approach to the design of moulds for expanded polymer parts was presented. The traditional tools used in steam-chest moulding technologies were replaced by lighter moulds produced by the laser-powder bed fusion technology, with significantly reduced mass and optimized ability to homogeneously delivering the steam to the part volume.

Design and manufacturing concepts were discussed and the performance of the innovative solution was presented, showing remarkable reduction of cycle times and of energy consumption when compared to a traditional steam-chest moulding used to print the same product.

The adoption of metal additive manufacturing technology allows using new materials and creating moulds with complex and advanced shapes, that can be tuned for the needs of the specific manufacturing process. This new paradigm opens new opportunities for innovation even in apparently well consolidated industrial areas.

5. Acknowledgements

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