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Casting parts with metallic foam

Y. Gaillard, J. Dairon
CTIF (Centre Technique des Industries de la Fonderie), Sèvres, FRANCE

This article presents the processes developed by CTIF to make metallic foam-like structures by the foundry route. These processes are based on the "infiltration" technique, similar to conventional foundry techniques, in which a preform, a sort of porous core, is infiltrated with molten metal. By the way, complex shaped cellular parts with skins (intrinsically linked to the cellular structure) can be reproducibly manufactured.

1 Introduction

Many ways have been developed to make metallic foams since the first studies on these materials in the 1950s [1, 2, 3]. The most intuitive of them consist in introducing gas into a liquid metal, through out a porous plug or by adding a substance that releases gas. But however the gas is introduced, it is quite difficult to produce foams in which the pore size and distribution are homogeneous. Indeed, successful implementation of these processes requires the use of sophisticated injection or mixing systems [2, 3, 4] and the introduction of solid particles into the metal [2, 5, 6], without which the foam would be unstable. These particles, carbides or oxides that are often expensive, pose recycling problems and substantially affect the mechanical behaviour of the metal constituting the foam [7]. The final result is that the mechanical performances of the foams so produced may fall far below expectations, and the reproducibility of their structure and behaviour may be poor.

Another way to make "foams", less intuitive but more reproducible, is to pour a liquid metal into a porous network, of which pores have the morphology of a foam. Once the metal is solidified, the material constituting the network is removed, leaving a homogeneous open-cell metallic "foam" (more precisely, it's a foam-like structure because gas pores do not arise by nucleation and subsequent growth in the melt. But for conciseness, we will call "foam" such a product). This kind of technique, very close to foundry techniques, is called infiltration method or replication process. It has been studied and adapted by CTIF for a number of years to produce aluminium foams [8]. Ceaselessly improving these processes, CTIF now proposes three main technologies to manufacture metallic foams of various alloys (aluminium, copper, cast iron and steel). This article describes them and presents their abilities to make complex foam parts with skin.

2 Review of infiltration techniques

The basic principle of infiltration techniques [2] is resumed in **Fig. 1**:

- a preform, for example stacked balls, is placed into the mould;
- metal is poured into the mould and infiltrates the network of pores constituted by the preform;
- after solidification of metal, the preform is removed, leaving a foam-like part.

Infiltration techniques are differentiated essentially by the way the preform is made. For this, there are nowadays two widely used families of solutions [2].

In the first case, balls or aggregates, called "precursors", are placed loose into the mould. Since they do not occupy all of the space, these precursors form a network of interconnected pores, i.e. the preform (as example in **Fig. 1)**. When precursors are spherical, this network gets a topology similar to that of foams produced by introducing a gas into a liquid (whence the similarity of behaviour of the foams produced by the two ways).

In the second case, an open-pore polymer foam is used as lost pattern. The polymer foam is infiltrated by a ceramic slurry, then heat-treated to solidify the slurry and to burn out the polymer foam. The result is a network of pores having the same shape as the original foam, which can be then infiltrated by metal.

The preform must satisfy a certain number of criteria. In particular, it must not contain isolated islands of material so that it can be completely eliminated after the casting of the metal. It must also be made of a material that keeps its shape during the infiltration (i.e. that can withstand heat), but that can be destroyed after casting to leave pores. This condition of preform extraction after metal solidification is an obstacle to the implementation of the second family of solutions, because it is generally difficult to remove the ceramic without damaging the metallic foam [9]. This also explains why salt was the first material to be used as precursors [10] to make aluminium foams: in addition to having a melting point (801°C) higher than the temperature at which aluminium alloys are cast, it can be eliminated easily, by dissolution in water. Today, other materials are also used to make precursors, among them sand and "malleable" ceramics [11, 12, 13].

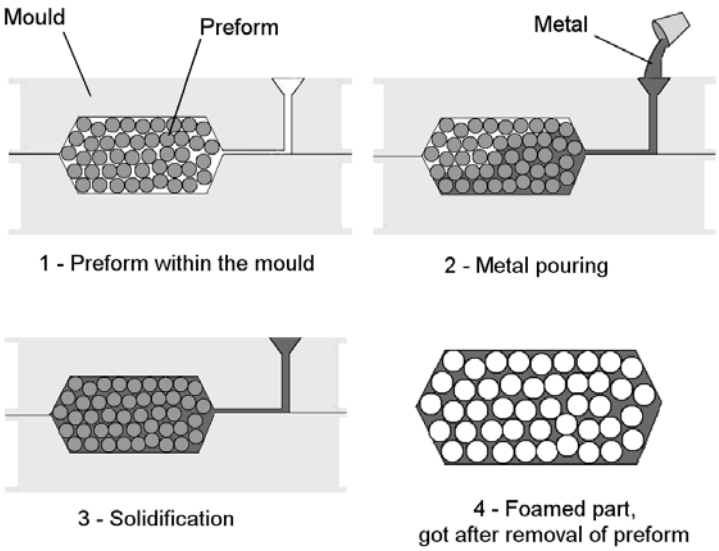

Fig. 1. Production of cellular metallic materials using a preform made of precursors.

3 CTIF's innovations in infiltration

CTIF has been producing aluminium foams for five years following the basic principles previously exposed [8]. Filling moulds with salt spheres and then pouring aluminium alloys, it manages to manufacture complex foamed parts, as those presented in **Fig. 2**. Porosity level of such parts is about 65%. Cell size can be fixed between 3 and 15 mm. Smaller precursors would impose preform preheating (that is expensive) to be infiltrated and it was found that larger spheres affect mechanical behaviour of foams.

Products so manufactured have a cellular structure that breaks to the surface, i.e. a skin with holes. This is because precursors are held in place by the mould walls themselves during metal pouring. These semi-finished parts are adapted to some applications (as energy absorption) but they do not satisfy the requirements of all industrial applications.

To meet other industrial needs, CTIF has developed foundry techniques to manufacture metallic foam structures surrounded by a skin made of the same alloy as the foam. For that, basic principles of infiltration techniques have been adapted in order to hold in place the preform all along infiltration step without contact with mould walls. Parts so realised are produced in a single operation, eliminating for example all the drawbacks of the insertion of a metallic foam core in a part (oxides, bonding defects, etc).

The developed techniques, hereafter presented, are adapted to a great number of metal compositions. They have been tested in particular on aluminium, copper, cast iron and steel. Like all infiltration processes, they require no specific addition elements in the alloy (SiC, oxides, etc), so that the products made are easy to be recycled. At last, following slight adjustments, they fit to conventional foundry processes, what will permit to manufacture cost-effective parts.

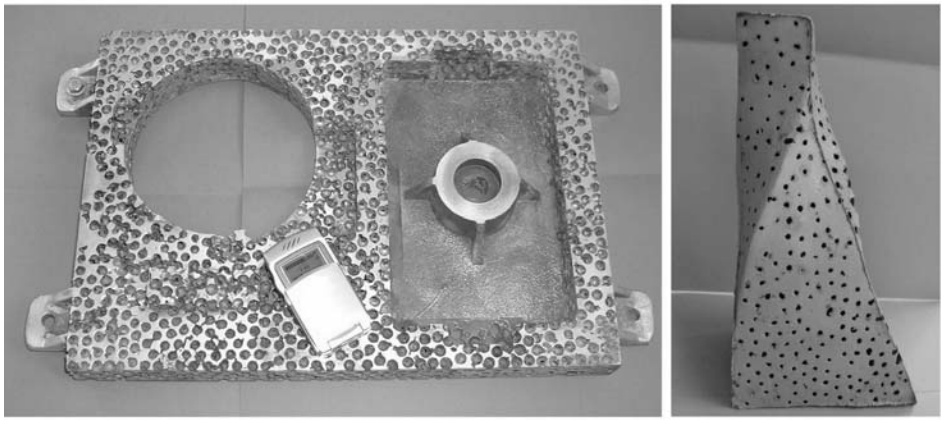

Fig. 2. CTIF demonstrators made of stochastic aluminium foam. [8]

3.1 Case of stochastic foam

Two techniques have been developed to produce parts with stochastic foam inside and with a skin around. For that, contact between precursors is ensured without leaning them against mould walls.

3.1.1 Precursors agglomeration technique

This technique [14] consists in agglomerating the precursors in advance to form a one-part preform, i.e. a porous core, which is then inserted into the mould (**Fig. 3**). This core must be strong enough at low temperature to allow handling, and at high temperature to withstand metal infiltration. In this goal, the best binder was searched.

Researches took into consideration parameters like the nature of the precursor material, the filling mode of tooling, and the size of the particles to be agglomerated. The study tested seven different binders or agglomeration modes: polyurethane resin (Pentex), furan resin, sodium silicate + CO_2, sodium silicate + ester, sodium silicate + stoving, polyvinyl glue, and epoxy resin structural glue. Two types of precursor were studied: glass, as reference, and salt, which can react with binders because of its ionic state. Finally, three sizes of precursors were used: spheres 5, 10, and 15 mm in diameter.

In order to quantify the mechanical strength at low temperature, a bending test was devised, using 40 x 40 x 160 mm prismatic specimens cast in a metallic tooling (**Fig. 4**). It is similar to the test used to characterize the mechanical strength of the binders of foundry sands. The prismatic specimens, intended to be broken in three-point bending, also served to judge the ability of the core to withstand handling. The mechanical strength was deemed sufficient if no sphere had come loose during reasonable handling and if the bending strength was exceeded 0.5 MPa.

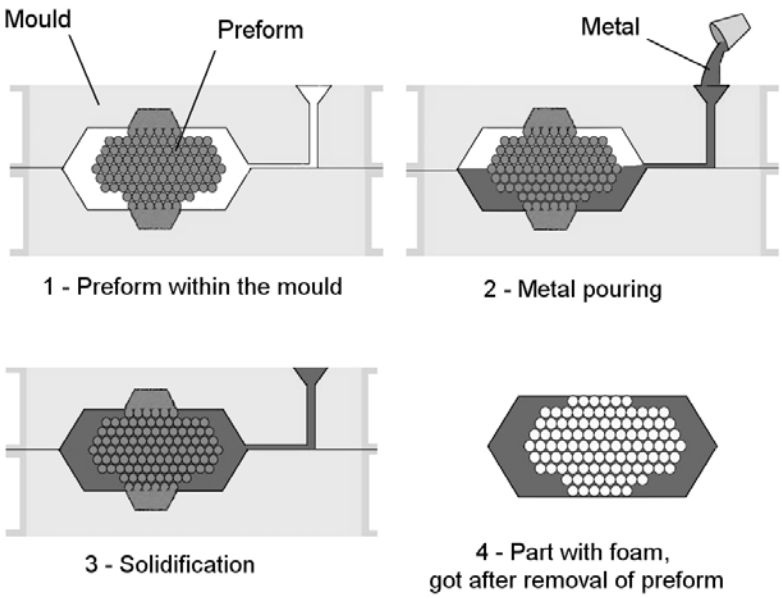

Fig. 3. Diagram of principle of the infiltration technique using agglomerated precursors.

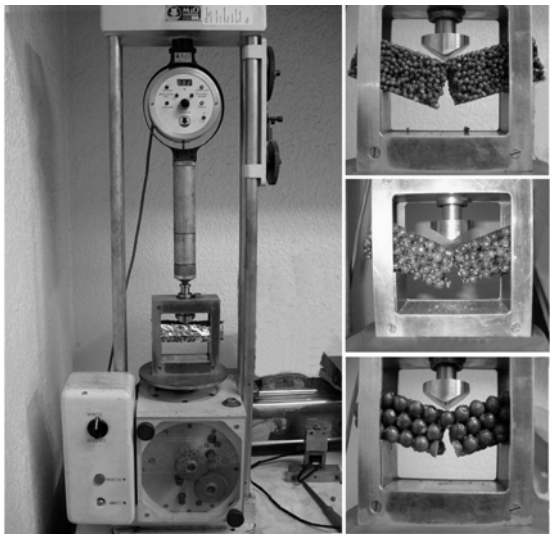

Fig. 4. Low-temperature bending tests. Left: the testing machine; Right: broken specimens with, from top to bottom: 5, 10, and 15mm spheres (salt + Pentex). Note the intra-particulate character of fracture (so binder is stronger than salt).

A summary of the most significant results (**Fig. 5**) shows that the classifications of the binders with glass precursors or salt precursors are similar, except for the case of epoxy resin, undoubtedly sensitive to the ionic state of salt. In addition, salt is less sensitive than glass to the diameter of the precursors, but its characteristics are substantially poorer. We also observed that the polyurethane binder has a certain plasticity not found with the epoxy resin.

Finally, because of binding performances, economical reasons and easiness of implementation, foundry binders are preferable: polyurethane for all diameters and stoved silicate for small precursor diameters. Moreover, the use of such binders permits to produce cores combining sand parts and agglomerated precursors, making complex industrial applications possible. Both ways have been optimized to limit the binder content while retaining adequate mechanical properties.

The agglomeration technique was developed for gravity casting, in a sand or chill mould, but pressure die casting tests have been very positive. The development work on the casting stage focused on the control of the kinetics of gas release, resulting from resin destruction, as well as the sizing and the holding of the core, to avoid deformations during infiltration.

Experience shows that, when possible, it is better to work with mineral binders than with organic binders; this eliminates the gaseous inclusions that affect foam quality. Large specimens (250 x 100 x 40 mm), representative of the major foreseeable foundry difficulties, were manufactured. They include in particular a core made of thin, brittle agglomerated precursors completely surrounded by a 5 mm web of alloy (**Fig. 6**).

The process possibilities in words of porosity level and cells size are the same as the basic process (**Fig. 1**). It can be used to realise complex castings, as it can be shown on right in **Fig. 6** that presents a part of an industrial prototype made by this process.

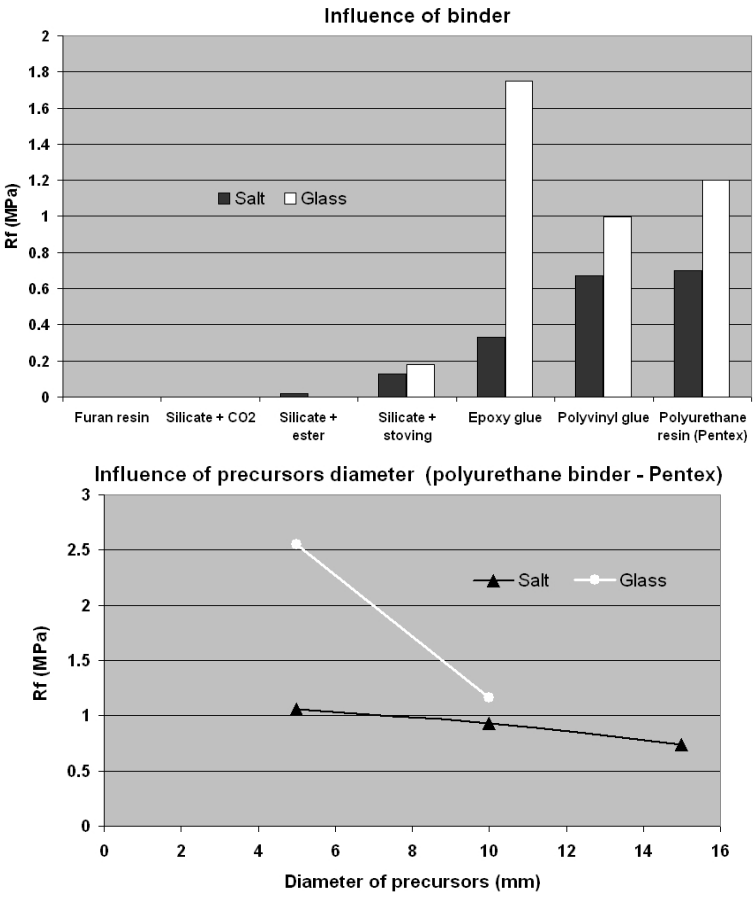

Fig. 5. Bending at low temperature: influence of binder (top) and diameter (bottom).

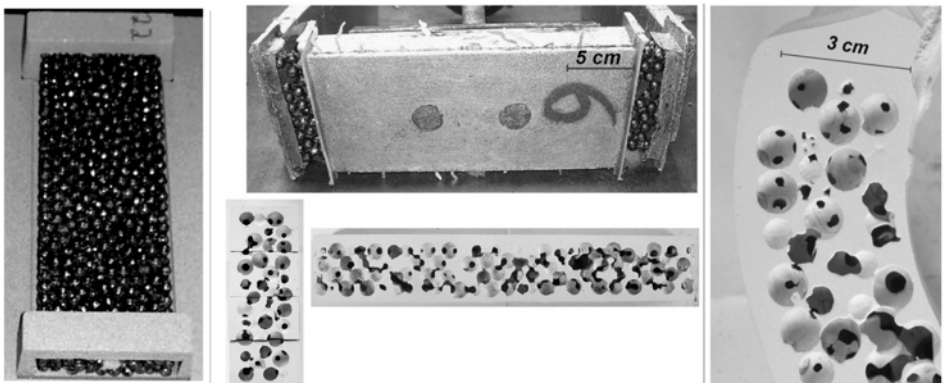

Fig. 6. Productions. From left to right: agglomerated preform, specimen, and edge of an industrial prototype.

3.1.2 Intermediate structure technique

In this technique [15], precursors are held in place by a thin external shell (3mm) through which gates pass (**Fig. 7**). This shell is made (for example, by a Croning process) in several parts that can be assembled, making it possible to place precursors inside. It is placed into the mould as an almost classic foundry core. Once metal is poured and solidified, the shell is eliminated with precursors. The part so manufactured is surrounded by a metal web that constitutes its skin.

This solution makes it possible to have a cellular structure that is adapted and controlled (in shape and size) between the aluminium foam and the casting. Various sizes and distributions have been tested, making it possible to claim that this process can produce structures adapted according to the forces and mechanical strength desired locally in the bond between the foam and the casting skin. As example, this bond can be adapted not to have a peak force in crash applications, sometime due to the presence of skin.

On the other hand, the technique requires accepting the intermediate structure presence, which is necessarily different from the foam structure. This drawback can be limited if the gating system is designed to guarantee a reproducible rigid structure between the foam and the external web.

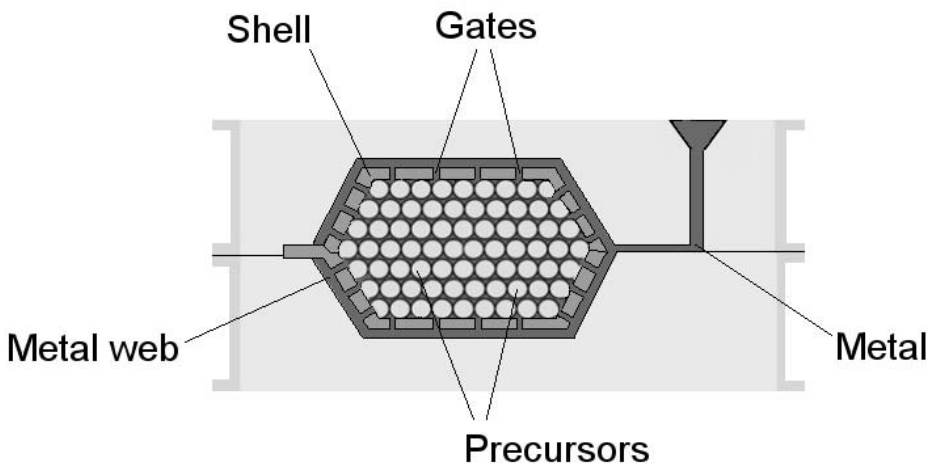

Fig. 7. Principle of the intermediate structure: part obtained after metal pouring.

Fig. 8 shows two parts manufactured following the intermediate structure technique. The first is a large prototype (110 mm x 60 mm x 230 mm), similar to the one manufactured by the precursors agglomeration technique (**Fig. 6**); the precursors used in making the prototype are 10mm spheres of salt. Here, used shell to implement the technique got cylindrical gates, so that the intermediate structure is columnar. The second part is a successfully manufactured industrial prototype, containing foam of which cells are 5 and 10 mm in diameter.

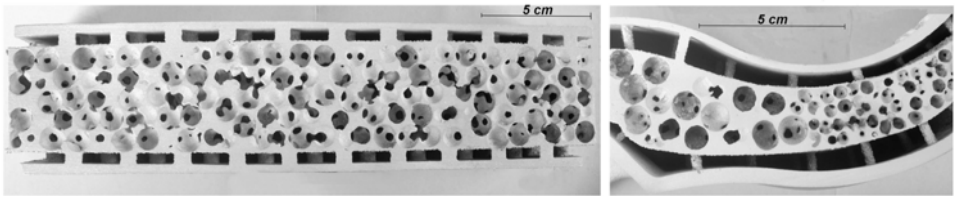

Fig. 8. Productions: left, prototype plate; right, edge of an industrial prototype.

3.2 Case of regular foam

During more than one century (until 1994), Kelvin's structure (**Fig. 9**) has been considered as the model of perfect foam [16]. Indeed, its periodical BCC structure, made from identical cells (Kelvin's solids, **Fig. 9**), respects the foams local laws (Plateau's laws) and has a very low surface energy. As a consequence, this structure is commonly used to model mechanical and functional behaviour of foams, (e.g. [17, 18, 19, 20]), with a good accuracy.

The hereinafter technique has been developed in partnership with Ecole Centrale de Lille [21, 22] to manufacture metallic foams with Kelvin's structure, in order to get products with a typical foam-like and predictable behaviour. In this technique, the preform is composed of stacked Kelvin's solids of which the edges have been chamfered (**Fig. 9**). So, the obtained porous network gets the desired Kelvin's structure to be infiltrated by metal.

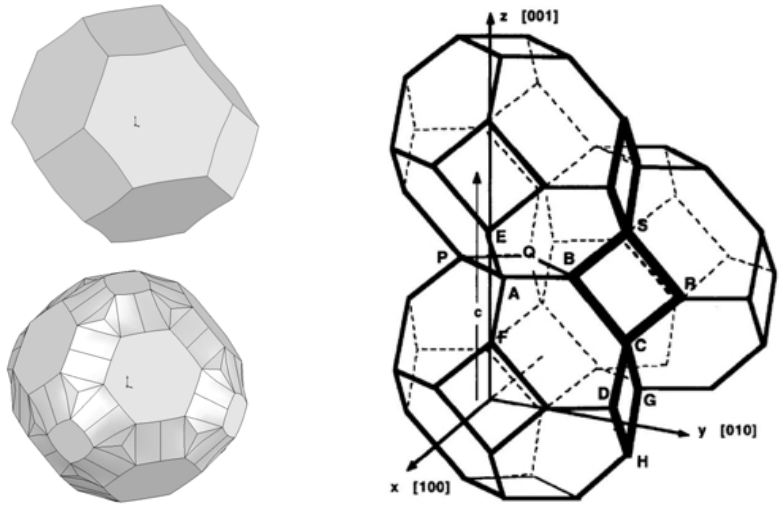

Fig. 9. Left, up: Kelvin's solid (tetrakaidecaedron with slightly curved edges of identical length) [21]
Left, bottom: Chamfered Kelvin's solid [21]
Right: Kelvin's structure [17], which is body-centred cubic

For the technique being cheap, Kelvin's solids are of course not stacked one by one. The astuteness consists in manufacturing plates of Kelvin's cells and then stacking them to constitute a preform, as show in **Fig. 10**. Few plates, each containing dozens of cells, are enough to build a preform. These plates are realised in agglomerated sand, using a core box and well-known and fast core blowing facilities.

Plates are not necessarily square; they can be manufactured to get any outline, by adapting the core box. They can also be machined one by one or as a whole. Consequently, preforms with complex external shapes can be realised.

The preform so obtained is ready to be inserted into the mould, as a classic foundry core. Then, the remaining stages of the process are identical to those of **Fig. 3**. After metal pouring, heat coming from metal cooling gradually burns the resin that binds sand particles and makes them loose. So preform removal is easy.

Fig. 11 shows the structure of periodic foams and a demonstrator obtained with this technique. Both have a porosity level of 85%. This one is fixed by the core box and can range from 80 to 90%. The size of the cells can also be fixed, but for cost reasons it is preferable that it should be larger than 10 mm. Below this value, production of the preform would be long, the level of rejects would be high, and the size of the parts that could be made would be very limited. This technique is used primarily in gravity casting in sand or chill moulds.

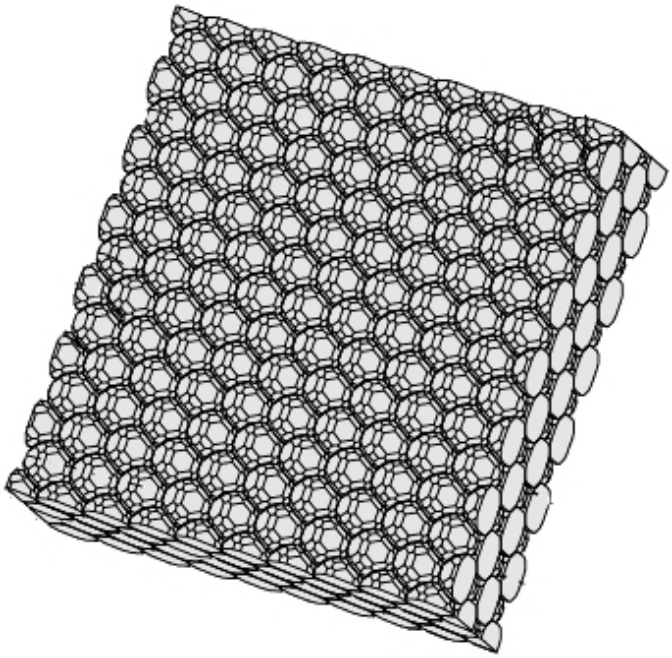

Fig. 10. Preform composed by stacked plates of Kelvin's solids.

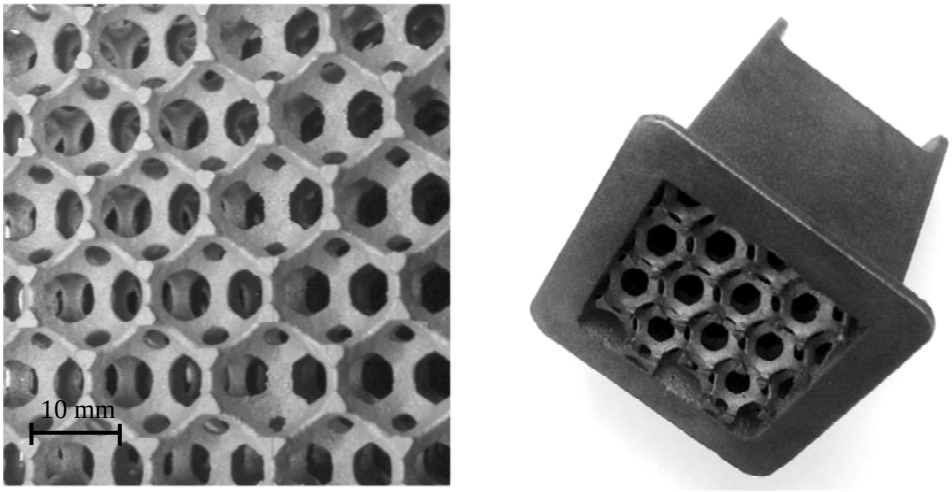

Fig. 11. Left: Periodic structure of 304 L stainless steel foam (level of porosity: 85%) Right: Demonstrator made with skin.

4 Summary of CTIF's processes advantages and applications

Foundry techniques developed by CTIF to manufacture metallic foams present several advantages. In addition to the control of cellular structure characteristics (pore size, porosity level, etc.), parts manufactured can have complex shapes and can get a skin quite easily. Since this skin is made at the same time as the foam, no additional step is required. Furthermore, the skin is intrinsically linked with the cellular structure. This material continuity is often essential, for example in thermal exchange applications, where any interface can deeply affect efficiency. Finally, a casting that is partially cellular and partially "solid" is also conceivable, making it possible to place a foam structure only where it is needed.

Metallic foams have many applications. But given the nature of industrial demand, the applications of CTIF products have mainly been in the areas of energy absorption (crash impact), vibration damping and thermal exchange (made possible by the openness of structure). Several industrial prototypes have been made, mainly for confidential applications. **Fig. 12** shows two demonstrators realised for not confidential applications.

5 Conclusion

Metallic foams are outstanding materials, due to their light weight, energy absorption capacities, thermal exchange properties, etc. But to meet industrial demand, it is often needed that parts containing this material get a skin. Foundry techniques developed by CTIF bring solutions adapted to this demand and make it possible to manufacture complex parts.

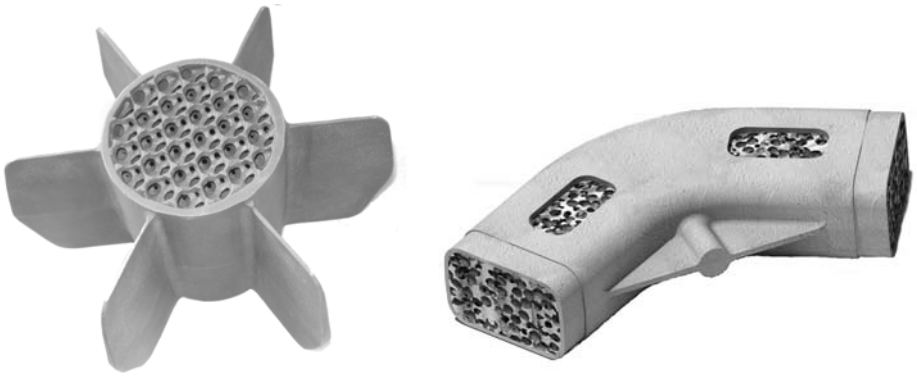

Fig. 12. CTIF functional demonstrators. Left: copper thermal exchanger (regular structure). Right: 3D view of an aluminium impact absorber (stochastic structure).

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