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Manufacturing process effect on the bending characteristics of titanium-lattice/FRP hybrid structures

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Abstract

High performances in terms of mechanical properties and lightweight are increasingly required to materials, and a solution to meet these requirements is the adoption of innovative hybrid structures made of metallic lattice core and composite material skins. In this work, two different processes are analysed and compared: co-curing and bonding. In the former case, the prepreg layers are laid up directly on the lattice, which acts as a mould. Instead, in the latter case, a composite material laminate is cured alone, and then it is bonded to the core. The aim of the work is to compare the flexural properties of the laminates obtained through the two abovementioned processes. Both types of specimens demonstrated a similar stiffness, but the co-cured one presented a higher strength, with an improvement of about 10%. This finding, coupled with the greater process ease, makes co-curing the best technological solution.

Keywords: EBM printing; Composite material; Bonding.

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1. Introduction

Higher performances in terms of mechanical properties and lightweight are increasingly required for materials used in the transportation field, as stated by Koziol (2019). A solution to meet these requirements is the adoption of innovative hybrid structures made of metallic lattice core and composite material skins, because both of them are characterized by high specific strength and stiffness. These peculiarities are synergically increased when they are combined together, giving rise to a more performant material. The outstanding mechanical properties typical of lattice structures are due to their particular design; in fact, they are made of several beams regularly positioned in space, as explained by Bellini et al. (2021). The lattice structures can be categorized according to the characteristics of their cell, that is the base unit of beams whose repetition gives the structure, as stated by Bellini et al. (2022). For making lattice core, several conventional processes can be taken into account, such as machining, filament winding, and casting, as stated by Bellini and Sorrentino (2018), Fan et al. (2010), Queheillalt et al. (2008). However, also innovative ones can be used, like additive manufacturing, due to the quality degree that this process can reach, coupled with the capability of manufacturing complex shape parts, as suggested by Dong et al. (2017). Even if the manufacturing process may cause some defects in the material, today post-processing procedures are suitable to lessen this issue, as indicated by Benedetti et al. (2021) and Razavi et al. (2021). The technical solution investigated in this work, that is the construction of lattice cored structures with FRP (Fibre Reinforced Polymer) skins, is quite convenient from the point of view of processing, compared to honeycomb. As explained by Bellini et al. (2021), the common honeycomb cores must be shaped by the milling process if complex shape parts are to be produced, but this operation may damage the core itself.

Several researchers have investigated the mechanical properties of lattice structures made through additive manufacturing technologies and their findings have been reported in different publications. To determine the manufacturing limitations, Leary et al. (2016) made lattice structures varying some geometrical factors such as beam diameter and cell type, then they tested the produced structures to find the obtained mechanical characteristics. Lampeas et al. (2019) implemented a numerical model to investigate the relationship between failure mechanism and process parameters in additive manufacturing processes. Epasto et al. (2019) produced lattice structures with various unit cell sizes, then they detected that the lattice with the largest cell had the worst mechanical behaviour. Applying the X-ray computed tomography, Liu et al. (2017) studied process-induced flaws in a lattice structure, then tested the structure and linked the defects to the failure cause. To enhance the crush behaviour, Mahbod and Asgari (2019) proposed lattice frameworks with functionally graded porosity.

Compared to other commercial cores, like honeycomb, lattice core is more rigid, but the loads applied to the structure are not uniformly distributed, due to the particular topology of the lattice. For this reason, skins are required. The simpler approach for achieving this objective consists in producing both the skin and the lattice core together; in such a manner, both the skin and the core should be made of the same material. This represents a very practical solution from a manufacturing point of view since the whole part can be produced within a single process; however, it may not be the best one in terms of performance, especially in terms of strength/weight ratio. For this reason, lattice structures with FRP (fibre-reinforced polymer) have been proposed. In fact, composite material is more lightweight compared to metal, without decreasing the mechanical performance.

In this work, two different processes to connect the skins to the lattice core were analysed and compared: co-curing and bonding. In the former case, the prepreg layers were laid up directly on the lattice, which acts as a mould. Instead, in the latter case, a composite material laminate was cured alone, and then it is bonded to the core. The former resulted to be more convenient since a single step is sufficient to obtain the part, especially in the case of complex shape parts. On the other hand, the latter allows the cure of the laminate on a dedicated smooth mould, improving the quality of the laminate itself. The aim of the work is to compare the flexural properties of the laminates obtained through the two abovementioned processes.

2. Materials and methods

The attributes of the lattice structure are very important since they affect the mechanical properties of the entire structure. As regards the cell type, the octet-truss one was chosen. This cell can be classified as a face centred cubic, composed by 12 struts, with an octahedron inside, as visible in Fig. 1. The cell side was selected equal to 6 mm, while the truss diameter to 1 mm: these dimensions were stated thanks to several tests aimed at evaluating the easiness of unmelted powder removal. The section of the produced lattice core was 30 mm x 9 mm, while the length was 168 mm, and the skin thickness was equal to 1 mm. The titanium powder used to produce the cores was made of the Ti6Al4V alloy, that is the most employed in the aerospace and aeronautic fields. As concerns the skins, they were made of carbon fabric and epoxy resin. A structural adhesive commonly used in the aeronautic field was adopted to improve the interface between the composite and the titanium. These specific types of prepreg and adhesive were chosen in order to adopt the same curing cycle for both of them, that is a condition needed for the co-curing process.

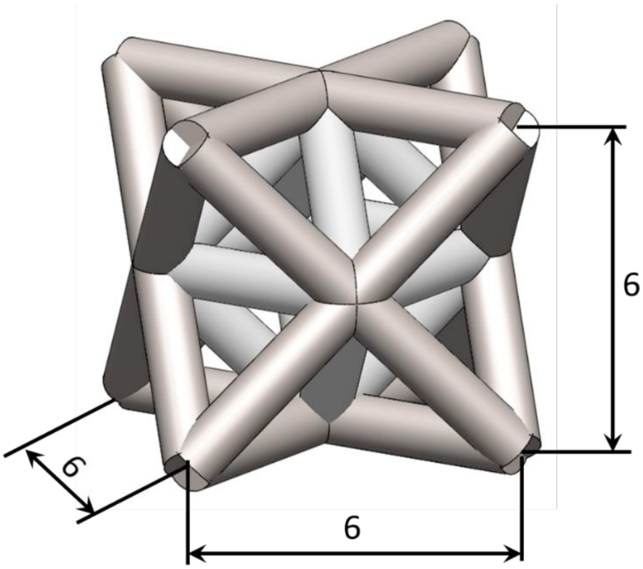

Fig. 1. The octet truss cell and its dimensions.

After having defined all the geometric parameters of the cores, the virtual geometrical model of the same was created by using the Materialise Magics software, that was able to draw a lattice structure in a specific volume, starting from the dimensions of the parallelepiped representing the core, as well as the type and strut diameter of the cell. Then, the 3D printer, an ARCAM A2X, was prepared for the manufacturing run: the powder reservoirs were filled and the process parameters were set. Then, the vacuum was drawn in the manufacturing chamber, the electron beam was calibrated and the manufacturing chamber was preheated at 700 °C. As the preheating temperature was reached, the specimens were built according to the typical sequence of a powder bed additive manufacturing process. When the cores had been built, the chamber was cooled down and the specimens were extracted from the unmelted powder and cleaned in a suitable chamber, using pressurized air and an ultrasound bath. An instance of the manufactured core is reported in Fig. 2.

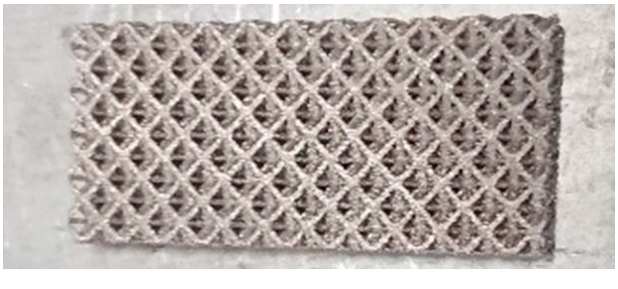

Fig. 2. An occurrence of the produced core.

Then further steps were required to add the composite skins. As concerns the co-curing process, FRP prepreg plies were prepared and layered on the mould, together with the lattice core and the layers of adhesive. The number of prepreg plies was chosen in order to obtain a thickness of about 1 mm for the face sheets, so 5 plies were necessary. All the layered specimens were covered with the release film and the breather fabric, then the mould was closed with the vacuum bag. After the vacuum was drawn, the mould was positioned in the autoclave for the curing process.

As concerns the second solution for adding the skins to the lattice core, that is the bonding process, different steps were necessary compared to the previous one. After preparing the prepreg plies, they were laid on a solid mould and cured. In this case, the vacuum bag process was considered, and a wider laminate was produced. Then, the laminates with the right dimensions for the skin were extracted from the wider laminate by cutting. These skins were bonded to the cores by using the structural adhesive. For this operation, a further thermal cycle was needed for curing the adhesive, so the preparation of a second vacuum bag was necessary. It is evident that the bonding solution is more expensive than the co-curing, in terms of time and resources, since a second cure cycle must be carried out. The produced specimen can be seen in Fig. 3.

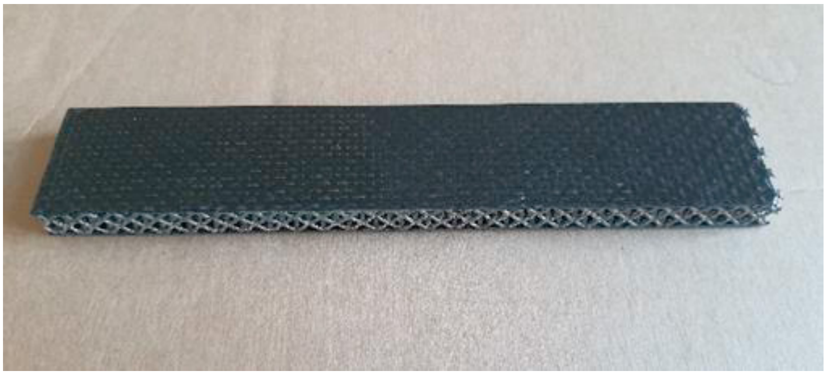

Fig. 3. The manufactured specimen.

Both types of the produced specimens were tested as per the ASTM C393, that is the standard for the determination of the flexural properties of sandwich panels. The specimen was placed on two supports and it was loaded in the centre by a loading nose, as visible in Fig. 4. The span length was chosen equal to 155 mm, while the loading speed to 5 mm/min.

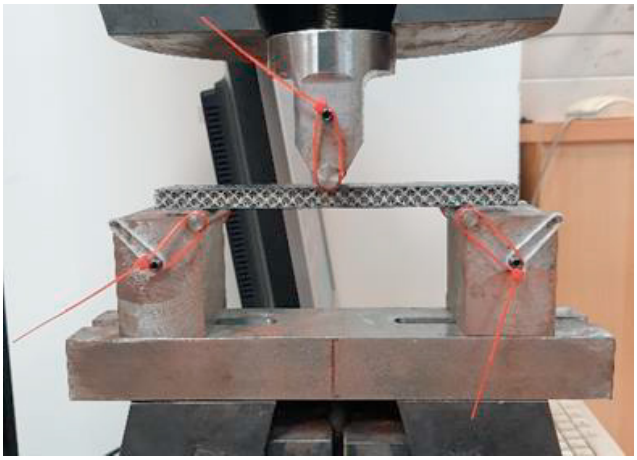

Fig. 4. The three-point bending test for the lattice-cored specimen.

3. Results

The data obtained from the experimental test campaign are reported in Fig. 5, where load vs displacement curves are plotted. From the experimental evidence, it can be noted that the highest strength belonged to the co-cured structure, that reached a maximum load of about 2700 N, while the bonded one presented a highest load of 2500 N. As concerns the maximum displacement, both structures presented a value of about 4 mm. As well as for the flexural rigidity, that was evaluated as the slope of the linear load increase tract: it was almost the same for both structures. Moreover, for both types, the linear tract was followed by a first load drop, due to the breakage of some fibres in the composite material, and the subsequent load increase was no more linear, due to the failure of other fibres. Therefore, if the first load drop is considered, the aforementioned maximum loads must be lowered of about 400 N in both cases. Finally, it is worth noting that after the overall maximum load, both structures presented negligible residual stiffness.

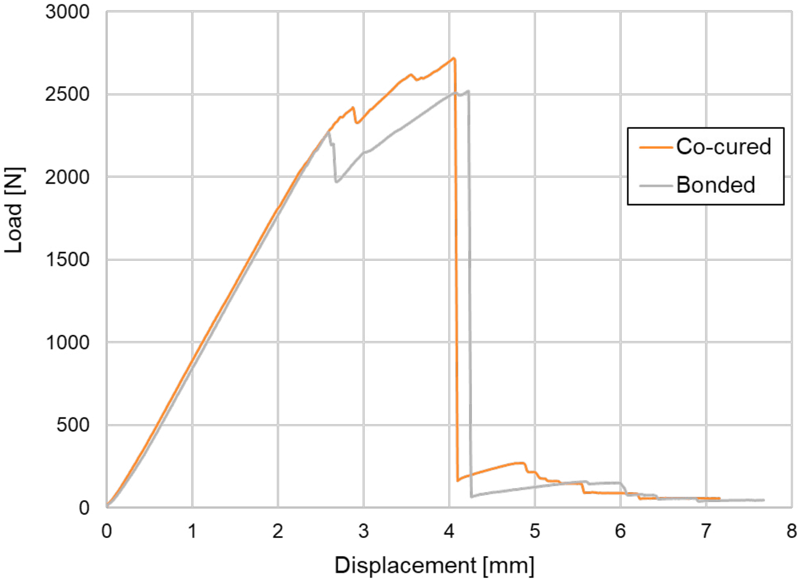

Fig. 5. Load-displacement curves for both the tested specimens.

4. Conclusions

The aim of the present work is to explore the effect of the manufacturing process, and in particular of the bonding solution, on the bending behaviour of metal lattice core structures. In particular, the CFRP skins were added to the titanium lattice core by co-curing process or bonding process. A two-step process was considered for the production of the specimens: at first, the cores were produced through EBM (Electron Beam Melting) process, and then the composite material skins were attached through autoclave vacuum bagging, according to one of the proposed processes. Then, the obtained specimens were subjected to three-point bending test to evaluate the flexural characteristics. As a result, the mechanical properties were found similar, even if a slightly higher flexural strength was found for the co-cured part. On the contrary, both the maximum displacement at break and the flexural stiffness were comparable. Therefore, it can be concluded that co-curing is to be preferred for the easiness and speed of the process itself, especially if complex shape parts are to be produced.

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