19th International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2025
Amsterdam, The Netherlands, Sep. 1st –6th, 2025

Microlattices with tailored properties as thermoplastic composite sandwich cores

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***Abstract* – Carbon microlattices demonstrate potential as substitutes for traditional honeycomb cores in aerospace applications due to their exceptional combination of ultra-low weight, high compression strength and stiffness. Integrating them into thermoplastic composite structures could be one of their first industrial applications. This study demonstrates that composites with carbon core materials can be realised and that carbon microlattices can be produced at a larger scale using commercially available stereolithography and sintering equipment.**

I. Introduction

Metamaterials are engineered materials that exhibit unique properties, owing to their intricate, repeating structures. These materials have significant implications for various fields, including aerospace, defence, energy, and biomedical applications [1]. Microlattices, in particular, expand the design space of metamaterials, allowing for greater detail and bespoke features. Moreover, they can approach theoretical strength limits at the nanoscale due to reduced flaw sizes [2] thereby achieving ductile behaviour in otherwise brittle materials [3]. However, producing such complex structures at small scales is a challenge.

Additive manufacturing, such as stereolithography (SLA) printing, offers a promising solution, but its scalability and resolution are limited for high-performance materials such as ceramics and metals. By combining high-resolution 3D printing with post-processing methods, e.g. sintering or pyrolysis, photopolymer green bodies can be transformed into carbon or ceramic microstructures with exceptionally high mechanical and thermal properties. Studies have established suitable pyrolysis cycles to greatly increase the compression strength and stiffness of SLA-printed samples through carbonisation [4]. Currently, this approach has however only been proposed at laboratory scale.

When produceable at larger scales, microlattices may become a promising substitute for traditional honeycomb cores in aircraft and rocket structures [5]. The combination of high thermal and high mechanical properties makes microlattices an attractive option for integration with thermoplastic composites processed at high temperatures and pressures. As part of a precursor study, we have demonstrated the viability of using carbon foam cores with automated fibre placement and autoclave consolidation (see Fig. 1). In this case, engineered 3D printed (micro)lattice cores may provide much higher mechanical properties and improved design freedom.

Fig. 1. Sandwich panel with carbon foam core and carbon fibre reinforced polyaryletherketone facing.

Within the context of this study, microlattice samples are manufactured using photolithography printing. Subsequently pyrolysis is utilised to create a carbon microlattice with exceptionally increased properties. These lattices are envisioned to replace the stochastic core materials previously used in thermoplastic sandwich panels.

II. Experimental Approach

Lattice samples have been fabricated using a Formlabs 3L vat photopolymerization printer. As feedstock material, Grey Pro resin, a photoinitiated urethane methacrylate compound, was used. Both Grey Pro as well as High Temp, another compound that is offered by the equipment manufacturer for higher temperature applications, were characterised using ThermoGravimetric Analysis (TGA), observing the weight loss of a sample of cured resin while heating to 900°C at 20°C/min under nitrogen atmosphere. A large residual weight at 900°C is an indicator for the suitability of the polymer for pyrolysis.

The microlattice's unit cell design is based on a diamond crystal structure arranged in a 10 abreast configuration to form a cube featuring an edge length of 23.3 mm. The strut length and diameter are 1 mm and 0.2 mm respectively. To achieve the high resolution required, test samples were made using the minimal layer thickness of 0.025 mm. A custom support structure was designed using thin pins, connecting the lattice to the solid support plate from which it could be easily removed after curing.

After fabrication, the test samples were washed to remove excess resin and left to rest for 24h to minimize deformation during curing and prevent the material from becoming sticky. Curing was carried out in a purpose-built oven for 1h at 80°C and UV light exposure. Thereafter, the cured polymer green bodies were pyrolyzed using a Xerion Fusion Factory Compact sintering oven. First, the samples were conditioned in aeriated atmosphere at 200°C for 1h. Then, under nitrogen, the temperature was increased to 350°C and held for 1h in the first trial and for 3h in the second trial.

Finally, the samples were inspected optically using a Keyence VHX-1000 digital light microscope.

III. Results and Discussion

Thermogravimetric analysis (see Fig. 2) demonstrates that the High Temp resin is stable up to 350°C, having a carbon yield of around 5%. Deterioration is observed for the Grey Pro resin from 150°C onwards with a negligible carbon yield at the end. These values are common for photocuring resins [6] and enable very high resolutions due to the large amount of shrinkage. They are however undesirable and unsustainable for larger scale production due to the very high material usage.

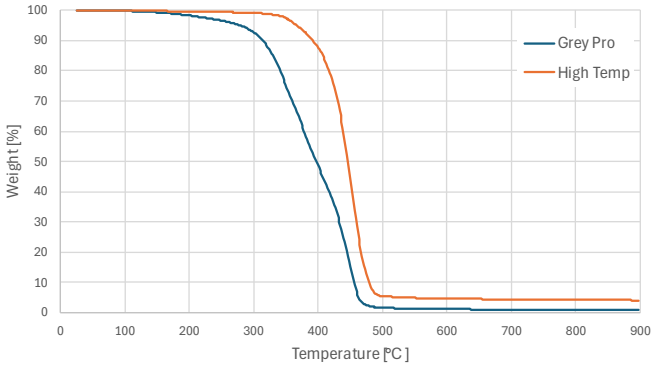

Fig. 2. Thermogravimetric analysis of the photopolymer resins

After the initial print, the fabricated samples exhibited a largely flawless lattice structure. Minor deformation of the cubes occurred both during curing and pyrolysis. Despite applying a resin-specific shrinkage compensation, minimal shrinking is observed after curing, with the width of the cube being 23.8 mm at the contact surface with the oven and 23.3 mm at the top of the cube. Pyrolysis results in shrinkage of the sample by about 40% after 1h of

exposure and 50% after 3h of exposure. The samples of the first trial exhibit a brown region at the bottom which was not seen after the prolonged 3h exposure. Likely, this region indicates reduced carbonisation with respect to the other parts.

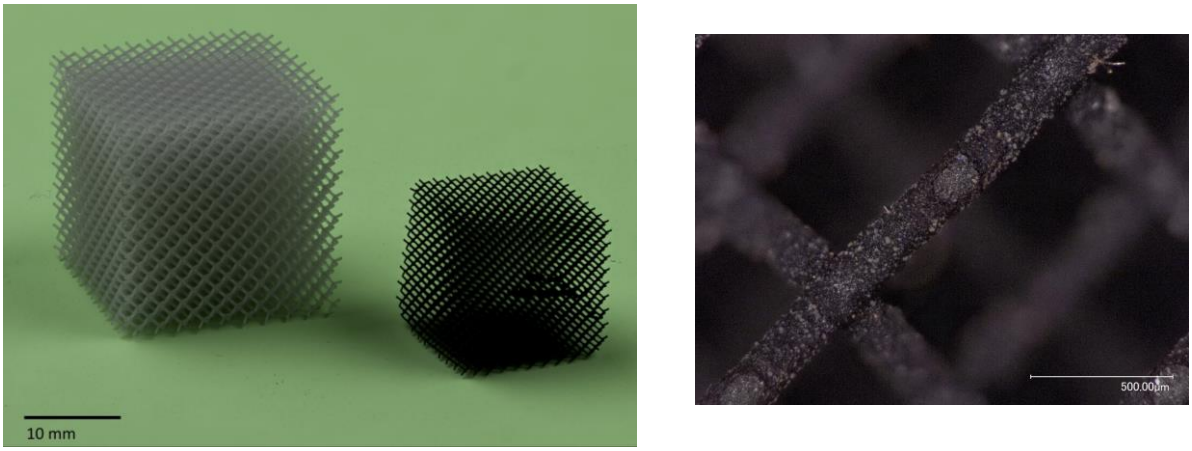

Fig. 3. a) Polymer precursor (left) and pyrolyzed microlattice (right); b) microscopy image of pyrolyzed lattice strut

The respective shrinkages observed during curing and pyrolysis both follow the same pattern, resulting in a frustum pyramid shape, in which the top surface of the cube is slightly smaller than the base and slightly convex. Gravity results in an increased shrinkage in the *z*-direction, while friction with the crucible obstructs shrinking in the *xy*-plane at the bottom of the cube, resulting in the wider base. Fig. 3 shows some impurities in the polymerised lattice, which are the result of improper washing. The optical microscopy images indicate a good level of detail in the lattice struts even after pyrolyis, showing that lower resolutions are possible.

IV. Conclusion

The pyrolysis of SLA printed polymer microlattices at 350°C was demonstrated to be possible at larger scale. Low pyrolysis temperatures of the same level as the processing temperature of high performance thermoplastic composites resulted in acceptable char yield and good product quality barring some non-uniform shrinkage.

Next, compression tests at elevated temperatures will be performed to evaluate the suitability for the envisioned application. Work in the near future will focus on improving the char yield, for instance by dipping the green bodies in a polymer better suitable for pyrolysis at higher temperatures. The net shape will be improved by compensating for shrinkage discrepancies.

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