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Behavior by design made possible by additive manufacturing: the case of a whistle-blower mechanical response

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Abstract

A pragmatic design strategy to achieve unusual mechanical responses in metal lattice structures is deployed. This strategy, referred to as *behavior by design*, is illustrated with an architected material fabricated to provide a “whistle-blower” mechanical response under tensile loading. Struts with unusual geometries, e.g. dog-bone struts and corrugated struts, are assembled in parallel in a standard lattice unit-cell to obtain the targeted elasto-plastic behavior, here a “whistle-blower” behaviour. The design strategy benefits from the freedom provided by additive manufacturing.

Keywords: Additive Manufacturing; Mechanical behaviour; Design; Architected materials

1. Introduction

The well-known *materials by design* approach is efficient to develop architected materials that fulfill a given set of requirements, which is difficult to meet in conventional materials, e.g. high strength and ductility, high strength and toughness, low density and high stiffness [1,2]. Often *materials by design* can fulfill several functions: mechanical, thermal, electrical, etc [1]. Here, we deploy a novel design approach, referred to as *behavior by design*, which aims to invent novel architected materials starting from their expected full stress-strain response [3]. This makes a clear difference from the *materials by design* approach where combinations of properties are the main target, not the shape of the whole stress-strain curve.

For architectures based on lattice structures, two main strategies can be considered: playing on the local connectivity (unit cell) or introducing struts with unusual geometries. Pham *et al.* [4] investigated the first approach. The authors relied on various hardening mechanisms inspired from metallurgy, (e.g. precipitation, grain boundaries hardening at the mesoscale of a lattice structure) to create robust and damage-tolerant architected materials with an assembly of simple unit cells using straight struts.

Another strategy is to consider struts with specific geometries to design unit cells exhibiting an unusual behavior. In our approach, the important morphological evolutions of the struts during deformation generate an unusual behavior. This new approach is attractive when the target stress-strain behavior exhibits an unusual shape that brings new functions to the material as shown in the examples in **Figure 1**. One can imagine among others:

- a “whistler-blower” behavior (**Figure 1a**), for which the structure presents a stress drop once a given stress σ_1 is experienced by the structure, and then the structure reacts appropriately by sustaining further stresses without leading to catastrophic failure.
- a “staircase” behavior (**Figure 1b**) with multiple stress-plateau that can be interesting in applications driven by energy absorption;
- a tunable stiffness (**Figure 1c**) which can be useful for applications requiring an adjustment of the vibration frequencies.

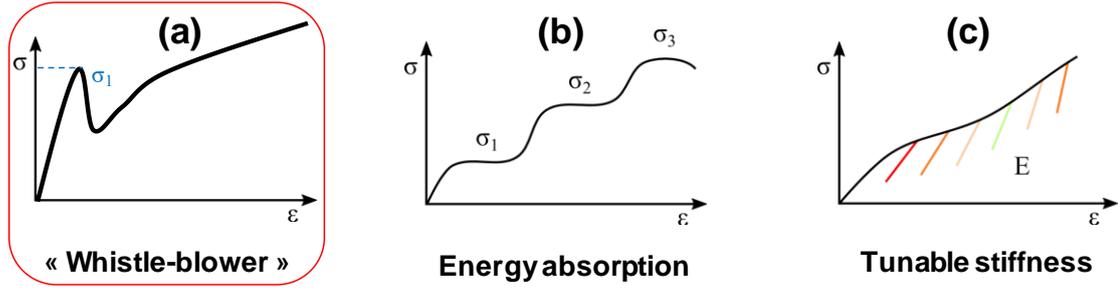


Figure 1. Examples of unusual stress-strain response. (a) “Whistle-blower” mechanical behavior. Stress-strain response (b) with multiple stress plateau for energy absorption and (c) for tunable stiffness.

In the present paper, we provide a proof-of-concept by designing, fabricating and testing a structure showing a “whistle-blower” tensile behavior. The present application is intentionally limited to a constitutive material with a limited strain hardening (Ti6Al4V-alloy) to highlight the geometrical effects induced by the introduction of struts with unusual geometries.

2. Design strategy

The first step of our design strategy consists of breaking down the target stress-strain response (**Figure 2a**) into a combination of elementary mechanical behavior assembled in series or in parallel (**Figure 2b**). The strut geometries are tuned to achieve the required elementary stress-strain responses.

Here, two different geometries of struts are employed: struts with a corrugated geometry (in blue in **Figure 2b**), and struts with a dog-bone shape with a central cross section smaller than the other struts of the lattice (in red in **Figure 2b**). Dog-bone struts will be the first to fail due to their limited straining capacity and will control the behavior of the structure at low strains. This is a *trigger-like* strut and its failure is controlled by adjusting the dog-bone central cross section. **Such strut geometry can be seen as a sensor in case of excessive loading conditions.** Corrugated struts provide a tunable strain-hardening through the concept of geometrical strain-hardening, initially introduced in [5] and further developed by others [3,6,7]. This can be considered as a *waiting element*. To our knowledge, this is the first time that the use of corrugated struts in lattice structures is suggested. The characteristics of the sinusoidal corrugation (diameter, amplitude and wavelength) were chosen based on previous works [3,8] that showed that the tensile response can be tuned on demand. The degree of geometrical strain hardening can be adjusted by tuning the main features of the corrugation [3,5,6].

In the second step, a unit cell is selected to obtain an assembly of struts in line with the decomposition into elementary behaviors (**Figure 2c**). In other words, the arrangement of struts in the selected unit cell allows the assembly of struts with various geometries to be made in series or in parallel. Here, the BCC-Z unit-cell containing vertical and 45°-oriented struts [9] (**Figure 2c**), is chosen mostly because it allows vertical struts with corrugated and dog-bone geometries to be assembled in parallel, but also because this unit cell appears well adapted to obtain the targeted mechanical behavior: initial stage of tension governed by vertical struts, connectivity of the struts enables large deformations by changing only a few struts, and central nodes makes easy the insertion of bridging elements. Such a strategy consisting of assembling elements in parallel was theoretically investigated in [10–12], and was implemented in the case of two macroscopic elements assembled in parallel [12]. Here, the tensile specimens consist of a stacking of three unit cells along the tensile axis and grips are added to make easier mechanical testing (**Figure 2d**).

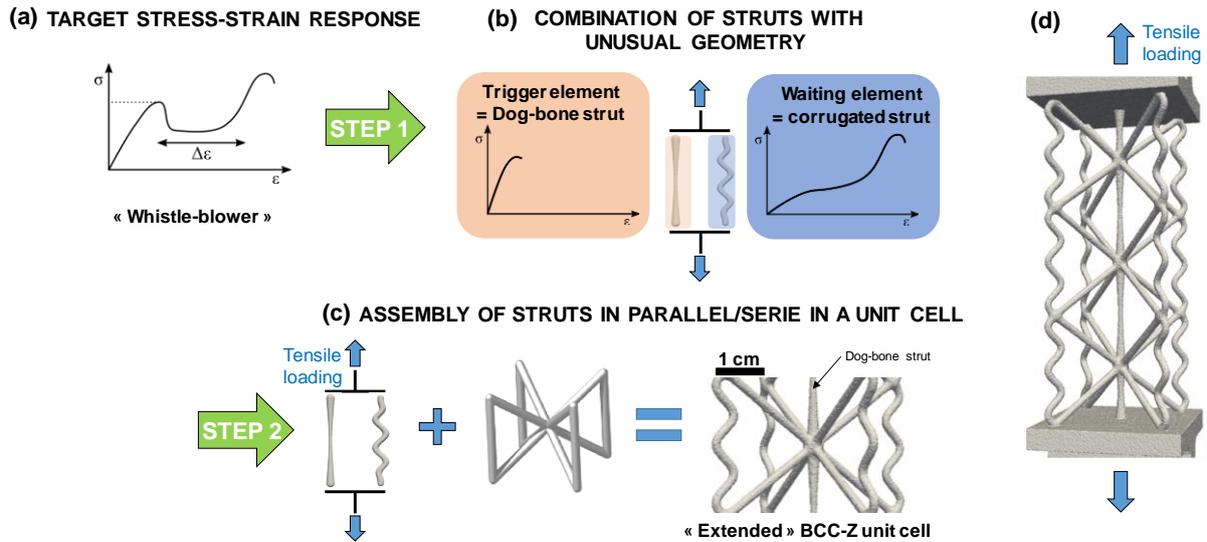


Figure 2. Summary of the design approach strategy. (a) Target stress-strain tensile response. (b) Step1: combination of struts with unusual geometries exhibiting elementary behavior. (c) Step 2: Introduction of struts with unusual geometries in parallel or in series into unit cell (BCC-Z here) to produce the “Extended” BCC-Z unit cell designed to generate a “Whistle-blower” mechanical behavior. (d) Final design of the tensile specimens for validation.

3. Materials and Methods

The structures were produced by Electron Beam Powder Bed Fusion (ARCAM A1 machine, 60 kV-accelerating voltage and 50 μm -layer thickness). Spherical powder particles of ELI Ti-6Al-4V (wt. %) alloy with diameters 45-100 μm were used. All samples were built in a single batch with the sample tensile axis parallel to the build direction. Standard melting parameters from the EBM control 3.2 software were used. The multi-spot strategy was applied for melting the contours (beam current of 4mA and 10 mA, and, spot time of 0.8 ms and 1.3 ms for respectively the outer and inner contours). The hatching strategy consists of moving the electron beam in a snake-like way to melt the interior of the struts with a beam current of 4.5 mA and a speed function of 98.

Two kinds of tensile specimens were produced. The first one is the BCC-Z structure whose vertical struts are corrugated with an additional vertical strut with a dog-bone shape that acts as a trigger to generate our “whistle-blower” mechanical behavior (**Figure 2c-d**). A second one, built for comparison, is a BCC-Z structure whose vertical struts are sinusoidal corrugated struts but with no vertical dog-bone strut. The diameter of the central cross section of the dog-bone strut is 1.5 mm in the CAD file. The CAD-diameter of the corrugated struts and their amplitude were set to 1.8 mm and 4 mm respectively (period was taken equal to 12mm).

After being printed, the specimens were first characterized by optical microscopy to investigate the microstructure in various struts and to assess its homogeneity within the lattice. X-ray Computed Tomography (XCT) was also used to characterize the whole lattice: geometrical dimensions of the struts and presence of defects. To reduce the harmfulness of those surface defects, the lattice specimens were chemically etched for 1h with a solution consisting of HF (48mL), HNO₃ (160mL), and, H₂O (1200mL) [13]. The etched structures were loaded under tension using a DY35 (ADAMEL) tensile machine equipped with a 20 kN load cell at a strain rate of 10^{-3} s^{-1} . An optical stereo-correlation system (Aramis GOM) was employed to measure the tensile strain.

4. Results and Discussion

The key to generate the whistle-blower mechanical response is to ensure that the corrugated struts can be fully unfolded. Given the constitutive material used in the present work, the Ti6Al4V alloy, two requirements for the lattice structures have to be met.

First, the microstructure within the lattice must (i) show the classical two-phase $\alpha+\beta$ microstructure of the Ti6Al4V alloy, and, (ii) be homogeneous. This is particularly important in the case of corrugated struts because a martensitic microstructure, typically observed in the as-built conditions when parts are fabricated by L-PBF [14], is very brittle and therefore would make difficult the unfolding of the corrugated struts. Struts having different geometries and located at different positions within the lattice structures were extracted to investigate the microstructure homogeneity. The microstructure was found to be homogeneous with the α -phase exhibiting a Widmanstätten morphology, see a typical micrograph from a corrugated strut shown as supplementary data in **Figure S1**. Here, we took advantage of the E-PBF process because contrary to L-PBF, no heat treatment is required to produce the two-phase $\alpha+\beta$ microstructure [14,16].

The second requirement is related to the geometrical characteristics of the corrugation (wavelength, thickness...) and the presence of surface notch-like defects. Strategies to ensure the unfolding of the corrugated struts were preliminary studied in [3] for the selection of the geometrical characteristics, and in [8] to evaluate the effect of surface defects. The geometrical features have to be selected appropriately because as-built parts made of Ti6Al4V exhibits a moderate elongation to failure (between 5 and 8%, see [16]) and this can lead to premature failure of the corrugated struts [3]. Besides, surface defects were proven to be detrimental for the mechanical properties, in particular for the fatigue life [15] but also in term of ductility (elongation-to-failure) [16]. The population of residual surface defects along single struts after chemical etching as well as their location along the corrugated struts was monitored based on XCT scans acquired subsequently to chemical etching, see [8] for a thorough analysis. It was shown that it is mandatory to avoid the presence of severe notch-like defects in the regions sustaining high tensile stresses, i.e. internal parts of the curvatures along the corrugated struts, because this can lead to premature failure before the strut is fully unfolded [8]. The objective of the chemical treatment was thus to decrease the harmfulness of those notch-like defects to make possible the unfolding of the corrugated struts as detailed in [8].

The stress-strain response of the structure with corrugated struts but without the trigger strut is given for comparison in **Figure 3a** and shows a similar tensile response as corrugated single struts. This illustrates that the work-hardening of a lattice structure can be tuned to a given extent thanks to the use of corrugated struts if one makes sure that the struts match the requirements discussed previously to be fully unfolded.

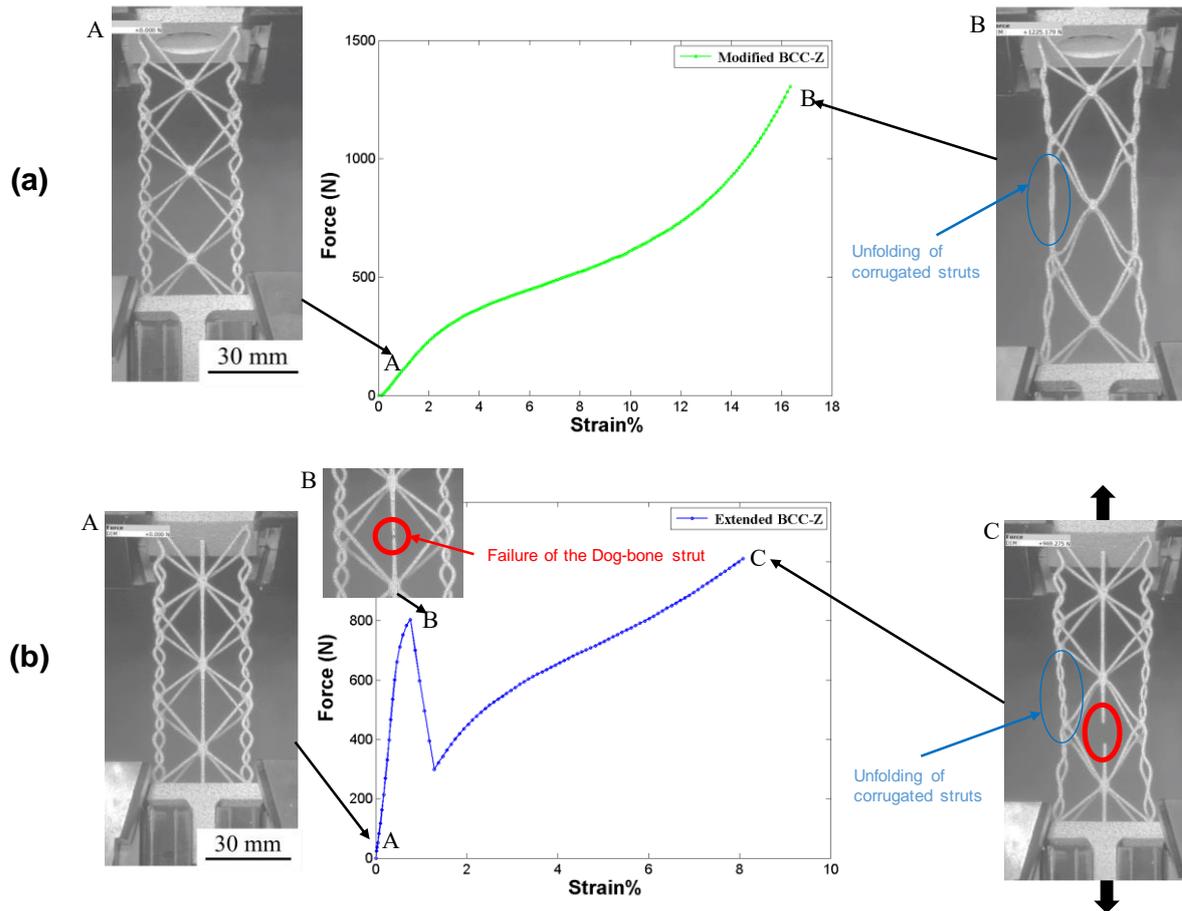


Figure 3. Tensile stress-strain response of (a) the BCC-Z with vertical struts substituted by sinusoidal corrugated struts, and (b) the designed structure with a « whistle-blower » behavior. Images taken at different strain increments are shown to illustrate the behavior of the structures at key steps.

The experimental stress-strain response of the “extended” BCC-Z structure is shown in **Figure 3b** along with images taken at different strain increments to monitor the sequence of events. The trigger strut fails when the force reaches about 800 N, then both the corrugated struts and the 45°-oriented struts sustain the load. The apparent strain hardening of this structure is governed by both the unfolding of corrugated struts and the re-alignment of the 45°-oriented struts along the macroscopic tensile axis. We benefit from the concept of *geometrical strain hardening* because the slope of the stress-strain curve in the plastic regime is induced by the architecture rather than the constitutive material (a Ti-alloy with a limited work-hardening capacity and a relatively limited ductility in particular when fabricated by additive manufacturing due to the presence of residual surface defects).

The generated mechanical behavior is close to the target, validating our pragmatic design strategy. If the target “whistle-blower” mechanical behavior is successfully achieved, one should note that this behavior can be further tuned on demand. The force at which the trigger strut fails can be adjusted by changing the diameter of the trigger strut. The subsequent mechanical response can also be tuned by appropriately designing the characteristics of the corrugated struts as done in [3] as well as the diameter of the 45°-oriented struts.

5. Conclusion

A novel design strategy consisting of assembling struts with unusual geometries in series or in parallel within a standard lattice unit cell has been successfully deployed to generate a “whistle-blower” mechanical response. To do so, dog-bone struts (*trigger elements*) and sinusoidal corrugated struts (*waiting elements*) are introduced in parallel in a conventional BCC-Z unit cell. The trigger strut can be tuned to make the structure react appropriately to overloads while the waiting element can be tuned to adjust the subsequent hardening of the structure based on the characteristic dimensions of the corrugation. This strategy opens new paths to the design of a novel class of architected materials and could be further refined by tuning constitutive materials properties or by accounting for coupling between individual struts behavior.

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