Additive manufactured break-out cores for composite production: A case study with motorcycle parts

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Abstract. To produce hollow-shaped, lightweight composite structures made out of fiber reinforced polymers (FRP), many manufacturing processes require a shape-giving tooling in form of a core. Additive manufacturing (AM) offers the potential to fabricate such tools and production aids with increased geometric complexity and functionality at reduced costs and lead time. An AM core can remain inside the produced composite part and provide additional functionality such as the integration of metallic inserts. A core can also be removed from the final composite part to reduce the part mass. To enable the removal of a core, a promising approach is to use AM to design and produce a core in form of thin-walled shell that integrates breaking lines. After curing of the composite part, the breaking lines are used to break and disassemble the core into smaller patches, which are removed through an opening of the cured composite part. To stabilize the core shell during composite production, it is filled with a filler material such as salt. Although AM break-out cores offer many benefits, only a limited amount of works exists that study such cores. Therefore, this work contributes novel concepts for the design of AM break-out cores. The focus lies on the use of perforated and continuous breaking lines to enable a controlled fracture of cores. A case study demonstrates their application to produce parts of a motorcycle including the flow intake and tank structure. After the case study, the work discusses possible improvements and outlines future research directions.

Keywords: Composite Production, Tooling, Pull-able, Peel-able, Removable, Break-out, Core, Additive Manufacturing, Motorcycle, Flow Intake, Tank.

1 Introduction

To produce lightweight composite structures made out of fiber reinforced plastics (FRP), many manufacturing routes require tools such as cores, mandrels, and molds [1]. Processes for production of FRP parts include autoclave curing, filament winding, braiding, bladder molding or resin transfer molding. In case of autoclave curing, tools such as cores are used as shape-giving elements to drape and cure pre-impregnated fiber material (prepregs). During curing of the composite part, the core must withstand elevated pressure and temperature conditions and provide sufficient support and stability to ensure the accurate production of the composite part.

Tooling aids such as cores can either remain in the final composite part or be removed after the production process. Integrating a core inside a part can have advantages for part production, assembly, and operation. The integration of cores makes it possible

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to increase part stiffness, integrate metallic inserts and interfaces, and position production aids [2][3][4][5][6]. However, cores that remain inside the produced composite part can also have disadvantages. They may not fulfill any function during operation and increase the part mass as dead weight.

Therefore, a number of prior works investigate cores that are used for production but are removed from the final produced composite part [1]. To remove a core from a cured composite part, one approach is to fabricate the core out of special materials such as low-melting alloys or dissolvable materials. After autoclave curing, this allows to remove the core as a sacrificial tooling through a washout or melting process. However, such materials are usually quite expensive, and a complete removal may take a long time or require special equipment. Another approach is to use inflatable or foldable cores that form a shape-giving tool under pressure. Although the release of pressure enables a fast removal, the attainable tool shapes can be limited. A further approach is to use a multi-piece tooling, which is assembled from multiple modules. A drawback is that the attainable tool complexity may be limited or require an increased number of modules thereby increasing the effort for tool assembly and disassembly.

A number of studies investigate additive manufacturing process (AM) [7][8] such as binder jetting (BJ), fused deposition modeling (FDM), and selective laser sintering (SLS) to fabricate removable cores. Prior studies utilize BJ of water-soluble sand [9] or FDM of dissolvable materials [10]. AM processes are also used to produce removable break-out cores [11][12][13][14]. In this case, a core is designed as a thin-walled shell that integrates breaking lines. After curing of a composite part, breaking lines are used to break and disassemble the core into smaller patches. The patches can be removed through an opening of the part. Prior works fabricate polymer-based break-out cores using FDM and SLS. To stabilize the core during autoclave curing, the core is filled with salt as a cheap and temperature-resistant filler material with a low coefficient of thermal expansion [9][15].

The use of additive manufactured break-out cores with integrated breaking lines offers many advantages. Firstly, break-out cores made from SLS or FDM do not require special materials, equipment, or the need for a re-melting or dissolution process. Secondly, the use of AM makes it possible to cost-efficiently produce break-out cores for hollow composite parts with complex-shaped geometry at a reduced lead time. Thirdly, AM break-out cores can provide design features to insert functional elements such as load introductions that are co-cured with the composite part. This enables the production of highly functionally integrated and lightweight composite structures.

Despite these advantages only a limited amount of prior works investigates AM break-out cores with integrated breaking lines. Therefore, this work aims to further elaborate on the concept of AM break-out cores and their application. After providing background information on the basic manufacturing route in Sec. 2, the work presents novel ideas for the design of break-out cores in Sec. 3. The focus lies on the design of perforated and continuous breaking lines. Sec. 4 demonstrates the application for the production of parts of a motorcycle that are made from autoclave curing of FRP prepreg material. Sec. 5 discusses the results and outlines necessary improvements for the design and removal mechanism of AM break-out cores. Sec. 6 finishes the work with main conclusions and future research directions.

2 Additive manufactured break-out cores

This section describes the basic manufacturing route that is utilized to fabricate complex-shaped composite structures using additive manufactured break-out cores that serve as a sacrificial and removable tooling. The manufacturing route is based on a number of preliminary works [9][12][15]. The main steps are displayed in Fig. 1.

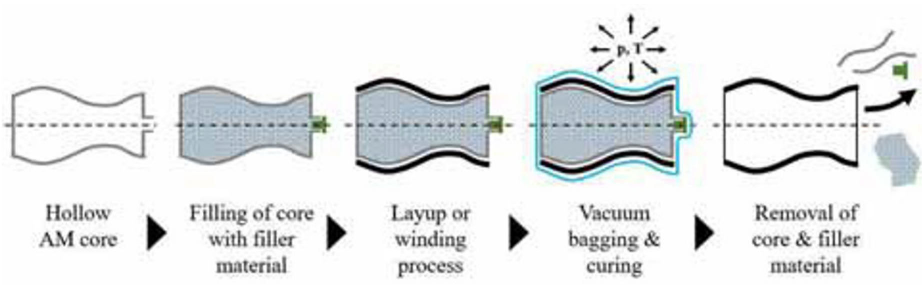

Fig. 1. Manufacturing route for the production of hollow composite structure using removable, AM break-out core that is filled with filler material during processing (adapted from [1]).

The first step consists in the design and fabrication of the core, which is used as a shape-giving tooling for the layup and curing of composite material. The core is designed as a hollow, thin-walled shell that integrates a number of breaking lines. Along the breaking lines, the core possesses a reduced wall thickness and notches to achieve a controlled fracture of the core along these lines. To fabricate the core, AM processes such FDM or SLS are employed. This allows producing a core with a complex-shaped geometry, which features breaking lines and can also integrate other design features, for example, to insert production aids or metallic load introductions and interfaces that are co-cured with the composite part.

In the next step the core is filled with a granular filler material that supports the shell during composite production and prevents a collapse or local deformation of the core. The filler material acts as a temporal support and is removed from the core after the curing steps. Prior works use salt as a cost-efficient filler material, which has a high temperature resistance, low coefficient of thermal expansion, and provides sufficient stiffness under compression. Based on its good flowability, salt also has the benefit to fill hollow spaces with intricate design features. After filling the core, it is enclosed with plugs. The filled core is further prepared by applying a release agent or release film. This prevents salt leaving the core and avoids a bonding between core and composite part, which allows separating and removing the core after the curing step.

In the following step composite material (e.g. prepreg) is draped on the core and cured in an autoclave. Alternatives for composite production are out-of-autoclave prepregs, filament winding, wet layup techniques, or resin transfer molding.

In case of autoclave curing, the next step includes bagging (e.g. adding of bleeder, breather, and release film) and curing under increased pressure and temperature to consolidate the prepreg. In the next step the part is unpacked, and the plugs of the core are opened to remove the filler material (e.g. washing out of salt).

To remove the core inside the composite part, the core is disassembled using the integrated breaking lines. The core is sequentially broken long the breaking lines into smaller patches, which are removed through openings of the cured composite part. For this purpose, the opening needs to be designed to provide sufficient access to crack and pull-out the patches. After core removal, the cured composite part is further post-processed. This includes milling of functional interfaces and finishing of part surfaces.

3 Design of breaking lines

AM processes such as FDM or SLS of polymers are suggested to fabricate the core as a thin-walled shell with integrated breaking lines that are utilized for core removal. The design of the breaking lines is crucial to achieve a controlled breaking and removal of the core from the inside of a cured composite part.

One key idea presented in this work is to use breaking lines in form of a perforated pattern of predetermined breaking points. As an example, Fig. 2 shows a tube-shaped, thin-walled core with perforated breaking lines. They partition the core into parallel-oriented patches. A close-up view displays main design parameters of the breaking lines. These include the gap width and bridge width of the perforated breaking line, wall thickness of the core, and reduced wall thickness along the breaking line.

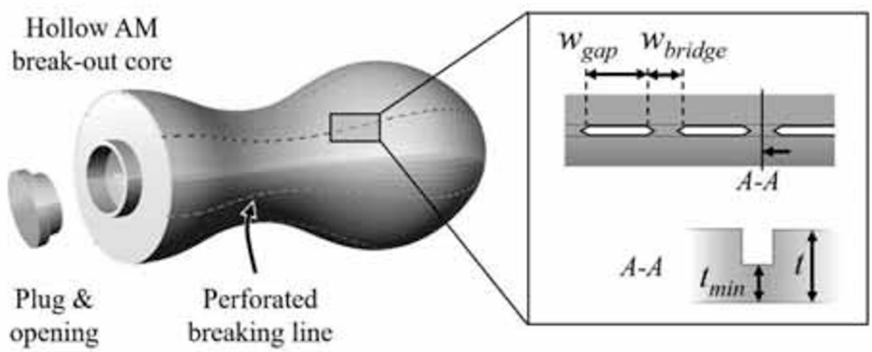

Fig. 2. Thin-walled break-out core with perforated breaking lines defined by of gap width w_{gap}, bridge width w_{bridge}, wall thickness t of core, and reduced wall thickness t_{min} at breaking line.

As a demonstration example, Fig. 3 (A) displays a simple test specimen. It is made out of ABS (acrylonitrile butadiene styrene) using FDM with a flat orientation on the build space. By pulling the patch a fracture is initiated, which propagates along the perforated breaking line as shown in Fig. 3 (B). The fracture mechanism corresponds to out-of-plane shearing and tearing (fracture mode III). The patch of the core is pulled using integrated leashes or peeled with pliers. The sequential pulling and removal of patches results in the disassembly of a core into smaller patches. These patches can be removed through an opening of a cured composite part. The opening of the composite part needs to provide sufficient access for core removal and pulling of patches.

Fig. 3. (A) Pulling of FDM-printed ABS patch with pliers; (B) Initiation and propagation of crack along predetermined, perforated breaking line.

The design freedom of FDM and SLS allows designing break-out cores with different shapes and configurations of breaking lines. Breaking lines can have various notch sizes, shapes (e.g. semicircular, U- and V-shaped notches), and perforation patterns. It is possible to use different layout strategies to partition the core into patches. Furthermore, one can leverage different fracture modes to pull and break the patches of a core. To decrease the number of patches that need to be removed, one promising approach is to design a core with a single continuous breaking line. As an example, Fig. 4 shows a test specimen, which integrates one continuous breaking line along a spiral-shaped pathway. Main design parameters are given in the figure and include the wall thickness of the core shell, wall thickness along the breaking line, and patch width.

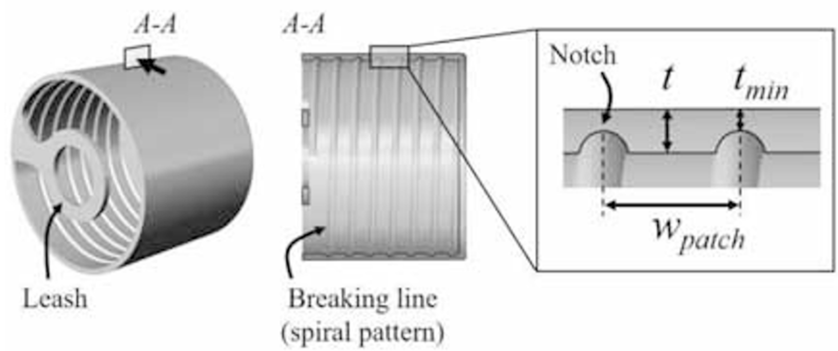

Fig. 4. Test specimen of break-out core with spiral-shaped breaking line defined by patch width w_{patch}, wall thickness t of core shell, and reduced wall thickness t_{min} along the breaking line.

Fig. 5 shows the test specimen with integrated spiral-shaped breaking line made out of polyamide using SLS. To break the core, a stress concentration and crack are initiated. By pulling the leash, the crack spreads along the breaking line. As shown in Fig. 5, the core is unwound as a continuous patch. The fracture mode along the U-shaped notch corresponds to opening (fracture mode I). With its reduced cross-sectional size, the patch shows flexible and spring-like properties. After the curing step, the idea is to use such a pulling mechanism of single patch can be used to remove the core from a cured composite part. The flexible properties of the patch make it possible to guide it through an opening of a cured composite part.

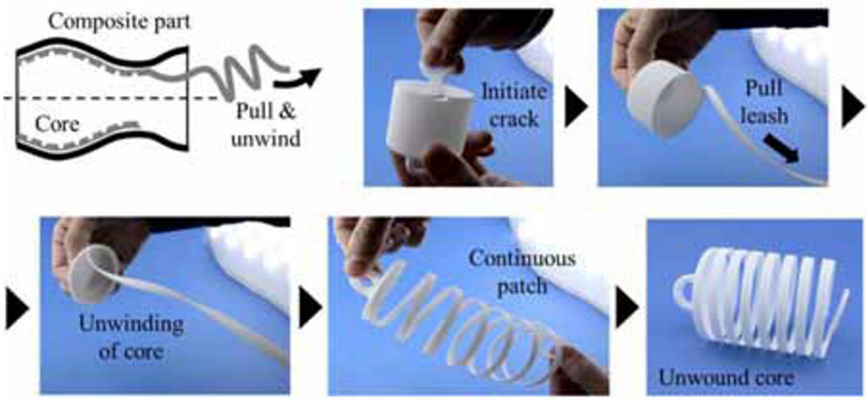

Fig. 5. Disassembly and breaking of SLS-made polyamide core by initiating crack and pulling leash to propagate crack along spiral-shaped breaking line and unwind core as a flexible patch.

4 Case study

The section demonstrates the use of AM break-out cores with perforated breaking lines to fabricate composite parts of a motorcycle, which is shown in Fig. 6. The examined parts include the flow intake and tank structure. The flow intake has the function to guide air into an airbox having an increased static pressure. The overpressure in the airbox increases the air flow rate into the engine and leads to an enhanced engine power. The tank provides a fuel reservoir of eight liters and is located in the rear frame of the motorcycle. To reduce the weight of the motorcycle, the flow intake and tank structure are produced using autoclave curing of carbon fiber reinforced polymers (CFRP) prepreg material. In the following, the production of the parts is described in detail.

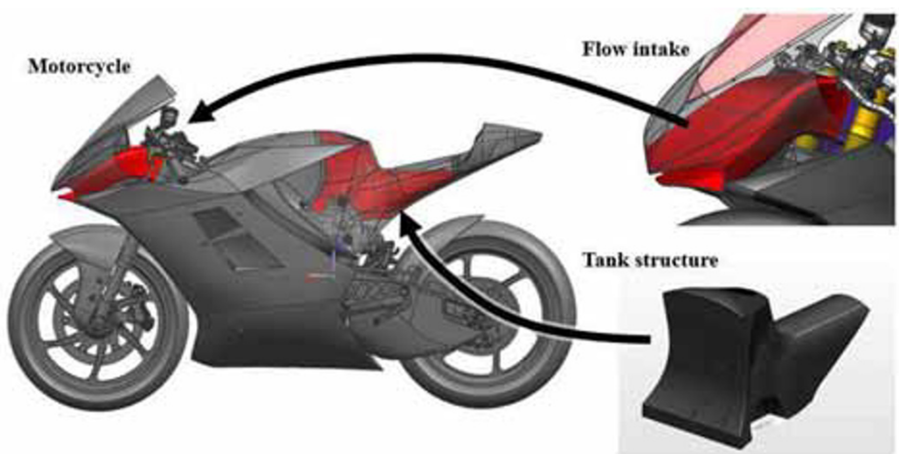

Fig. 6. Picture of motorcycle race bike developed by student team *ETH Moto Racing* (supervised by CMASLab of ETH Zurich) showing detailed view of flow intake and tank structure.

4.1 Flow intake

Fig. 7 depicts the production steps of the flow intake. Step 1 shows the thin-walled, break-out core, which has a wall thickness of $t = 2$ mm and contains a series of parallel oriented, perforated breaking lines ($t_{min} = 1$ mm, $w_{bridge} = 5$ mm, $w_{gap} = 7$ mm). FDM is used to fabricate the core out of ABS. The build orientation of the core is marked with an arrow. In step 2 prepreg sheets of twill fabric are cut for the layup, which consists of five layers on the top and bottom surfaces and seven on the side surfaces. The core is further prepared by applying a release film using glue. The release film prevents a bonding between the core and the prepreg and makes it possible to remove the core after curing the prepreg material. In step 3 the prepreg sheets are laid onto the core according to the layup plan. Further preparations include the application of additional release film, breather material, and vacuum bagging. To produce the flow intake, the core is not filled with filler material. Instead, given the two openings of the part the vacuum bag is set up in such way that it compresses the layup from two sides but does not deform and distort the shape of core. In step 4 curing of the prepreg is carried out at 84 °C for 12 h. After curing, the part is unpacked, and the core is fully removed by breaking the core into smaller patches using the breaking lines as shown in step 5. Some patches do not show a controlled fracture along the intended perforated breaking lines. In step 6 post-processing is applied such as milling and grinding of surfaces to get the finished composite part of the flow intake. The final flow intake part has a mass of 300 g.

Fig. 7. Visualization of production steps of CFRP flow intake using a break-out core that is fabricated out of ABS using FDM, prepared with release film, used for layup and curing of prepreg material, and removed after composite processing through integrated breaking lines.

4.2 Tank structure

Fig. 8 shows the production steps of the tank. Step 1 consists in the design of the core with perforated lines. The core is designed with a wall thickness of $t = 2.4$ mm and several perforated breaking lines ($t_{min} = 1.4$ mm, $w_{bridge} = 5$ mm, $w_{gap} = 7$ mm) that subdivide the core into smaller patches. After curing of the composite part, the patches are removed through an opening that is located at the tank bottom. It provides access to the internal tank structure. In the final part, the opening is used to connect the tank with the fuel pump of the motorcycle. In step 2 the core is fabricated in ABS with FDM. The core is produced out of five sub-parts, which are printed in different build directions and joined through adhesive bonding. In step 3 release film is applied on the core and it is filled with salt. To fill the core with tightly packed salt, a vibrating table is used. Besides filling the thin-walled core with salt, the core design is locally enforced with stiffening ribs. These measures prevent the core from being indented during autoclave curing. After filling with salt, the opening at the core bottom is sealed with a plug.

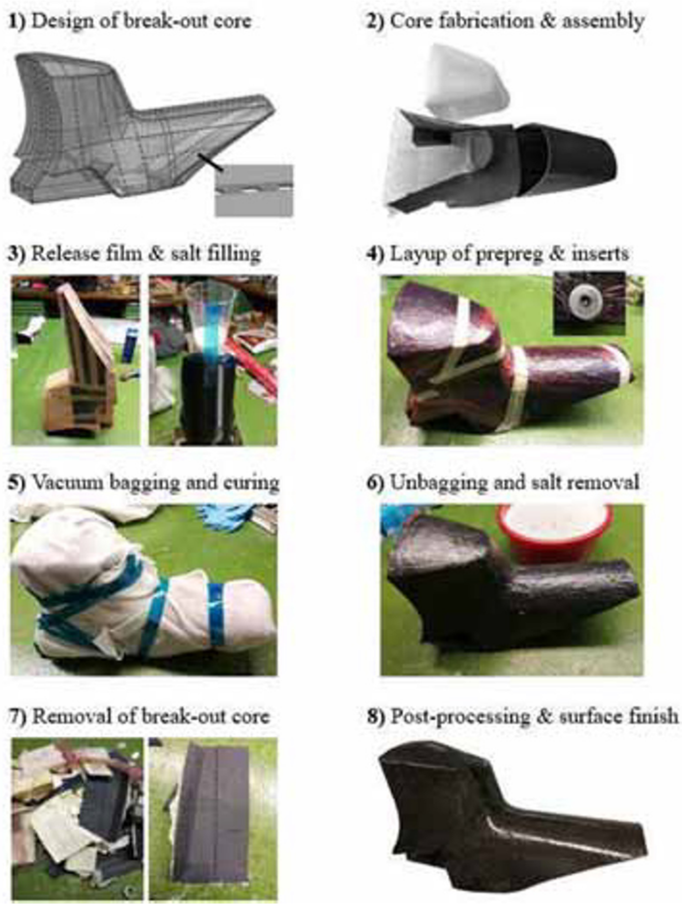

Fig. 8. Visualization of production steps of monolithic, hollow CFRP tank structure utilizing break-out core that is fabricated out of ABS using FDM, filled with salt as supporting material, used for layup and curing of prepreg material, and removed after processing of composite part.

As shown in step 4, metallic inserts are placed in the core. These are co-cured with the composite part and used to attach the tank to the frame. Also, the prepreg sheets are applied on the core. In step 5 release film and breather material are added before vacuum bagging. The composite part is cured at 84 °C for 12 h. It is then unpacked in step 6, and salt is removed by opening the core at the lower bottom of the tank and washing it out with water. Step 7 consists in breaking the core it into smaller patches using the integrated breaking lines and removing it through the opening. After core removal, the inner structure of the tank is cleaned with a solvent and sealed with chemically resistant epoxy. The final step 8 applies post-processing steps to the outer tank surfaces. Furthermore, functional surfaces are post-processed and milled (e.g. lower interface to fuel pump, upper opening towards fuel tank cap, integration of air vent). This leads to the final monolithic CFRP tank structure. The mass of the empty tank structure is 560 g.

5 Discussion

The case study demonstrates that AM break-out cores can be used for the production of complex-shaped, hollow composite parts. The salt-filled cores withstand elevated temperature and pressure conditions during autoclave curing. In both examined parts, the core is fully removed by breaking it along integrated breaking lines into smaller-sized patches. Main advantages of the approach are that it is accessible and does not require special materials, hardware or equipment. The approach is, however, still in an early development stage. At the current level of maturity, it is suitable for the production of prototypes, individualized composite structures, or small-series parts. Further improvements are required to achieve a controlled fracture and removal of cores.

For example, a number of patches do not show a fracture along the breaking lines. Instead a fracture occurs perpendicular to them and lies between printed layers defined by the build direction of FDM. Therefore, future works are needed to better understand the influence of AM (e.g. chosen AM process, parameters, material, build direction) on the fracture behavior. Processes such as SLS may be more suitable compared to FDM and reduce anisotropic effects caused by layer-wise manufacturing. To employ cores for increased curing temperatures, future studies may investigate the use of high temperature materials such as PEI (polyetherimide) or PEEK (polyether ether ketone).

Different concepts and mechanisms can be studied to achieve a robust and reliable removal and disassembly of AM cores. Future studies can investigate different designs and shapes for breaking lines and notches, other mechanisms for core removal (e.g. collapse of core under vacuum, use of wires for core pulling and fracture), multi-material AM (e.g. different materials at the breaking lines), or local modification of AM process parameters (e.g. porous material properties at breaking lines).

The design of cores with complex-shaped breaking line patterns (e.g. concept in Fig. 5) presents another bottleneck. Algorithms need to be developed that automate the design generation and layout of breaking lines based on a given input part geometry and constraints of a chosen AM process. In this respect, a simulation-based approach (e.g. extended finite element method, XFEM) may be used to predict and optimize a controlled facture and removal of AM cores.

6 Summary and outlook

This work examined additive manufactured break-out cores for the production of hollow-shaped, fiber reinforced composite structures. The cores are thin-walled and integrate breaking lines to enable their controlled fracture and removal from the inside of the cured composite part. To stabilize cores during autoclave curing, they are filled with a support material such as salt. This work contributed novel concepts for the design of breaking lines such as the use of perforated and continuous breaking lines. The work demonstrated the application for the flow intake and tank of a motorcycle. Future studies are necessary to achieve a fast and robust facture and disassemble of AM cores. To cost-efficiently implement the concept for series production, it is required to automate the design of cores, the removal and disassemble mechanism, and the layup of composite material (e.g. using filament winding, braiding, and fiber patch placement). Overall, a key idea presented in this work is to leverage the design freedom of AM processes to design structures in such a way that they exhibit a controlled fracture and breakage behavior. Besides AM break-out cores for composite structures, this concept may be applied for molds and tools for other forming and solidification processes such as casting, press forming, and injection molding as well as for mechanical parts that should rapture and collapse in a controlled behavior in response to a static or dynamic loading.

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