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Effect of honeycomb cell geometry on compressive properties: Finite element analysis and experimental verification

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Abstract

Metallic cellular materials are characterized by a low specific weight and a high energy absorption capability, which make them promising for application in devices of the transportation industry in order to meet the requirements of a reduced fuel consumption and carbon dioxide output. This intention necessitates the evaluation of material performance under several load conditions. Investigations have shown that the out-of-plane properties with regard to specific energy absorption (SEA) capability of high-density steel honeycomb structures with square-celled profile are outstanding while the potential under in-plane conditions is distinctly lower. Therefore, FEM-based numerical analyses are conducted by the use of ABAQUS-software to investigate the influence of cell geometry. The results reveal an enhancement of absorbable energy in in-plane direction by applying an ordered sequence of hexagons and triangles, the so-called Kagome geometry. Comparative quasi-static compression tests serve to verify the FE-analysis. The obtained results are discussed with respect to strength level and achieved SEA capability in dependence of the cell geometry and load condition.

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Keywords: Honeycomb; Finite element analysis; Cell geometry; Out-of-plane; In-plane; Specific energy absorption (SEA) capability

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1. Introduction

Recent studies showed that the out-of-plane compressive stress–strain behavior of high-density square-celled honeycomb structures made out of TRIP-steel is distinguishable in four characteristic sections. Initially, a linear-elastic region is formed, followed by a pre-buckling stage before buckling and structural collapse initiates. At elevated strain levels structural densification connects to the post-buckling stage [1,2]. The achieved high strength level, entailing a great energy absorption capability in this load direction, is traced back to the deformation caused predominantly by normal stresses along the loading direction [3,4]. In dependence of relative density, local or torsional buckling and global "Euler-type" buckling occurred, which lead to folding collapse and symmetric extensional collapse mode with plastic kink formation, respectively [1].

Contrary, a distinct decrease of strength can be measured if the axial force is applied perpendicular to the channel axis (in-plane). Under consideration of stress–strain progress, an absence of the pre-buckling stage has to be recorded so that the loss of stiffness and structural failure is directly connected to the mainly linear elastic region. Principally, the vertical struts are also subjected to axial stresses at the beginning of deformation. However, inhomogeneities caused by manufacturing like curved cell walls, pores or impurities lead to the onset of instable deformation. Bending moments are initiated in the cell nodes, which are adjacent to the imperfections, involving bending and rotation of cell walls. Thus, macroscopic failure is characterized by sequential shear of the several cell rows [4]. In literature, row by row destabilization was also observed for aluminum honeycombs with hexagonal cells [5] and square-celled profiles made out of maraging steel [6].

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Basically, the stiffness and the strength of periodic cellular structures depend on the dominating deformation mechanism namely cell wall stretching or bending. Which kind of mechanism occurs, is influenced by the cell geometry. For equilateral triangular cells, Kagome cells and diamond cells (transverse stiffened) with rigid joints preferable cell wall stretching was identified in in-plane mode. As a result, the collapse load depends mainly on the axial strength of the struts. Contrarily, honeycombs with hexagonal cells and rigid joints are occupied by the bending-dominated mechanism leading to a higher compliance and lower collapse strength as compared to stretch-dominated structures [7,8].

It cannot be assumed that cell walls of honeycomb structures with square cells, processed by a powder metallurgical extrusion process, are exactly aligned and consequently that bending-dominated deformation is avoidable in in-plane mode. Nevertheless, the replacement of square cells by cell geometries entailing a more stretch-dominated deformation mechanism seems to be promising in order to increase the strength and hence the energy absorption capability, which is essential for potential application in devices of the transformation industry.

In this study, FEM-based numerical analyses are conducted in first instance to identify a cell geometry with increased strength at different load conditions. Subsequently, a die for the extrusion process is manufactured according to the geometry with promising properties. The sintered honeycombs are investigated in quasi-static out-of-plane and in-plane compression tests in comparison to the structures with 14 × 14 square cells.

2. Finite element analysis

The FEM-based numerical analysis considers the load conditions of in-plane and out-of-plane compression. Final aim of the study is the identification of the cell geometry which provides the highest SEA capability at dynamic strain rates. A limiting factor for the selection of new cell geometries arises by the manufacturability via powder metallurgical extrusion process, requiring a cell wall thickness of at least 250 μm and preferable straight contours. Fig. 1 contains an overview of the nine investigated base profiles. Additionally, five of those profiles are analyzed by 90°-rotation due to their strong axial anisotropy.

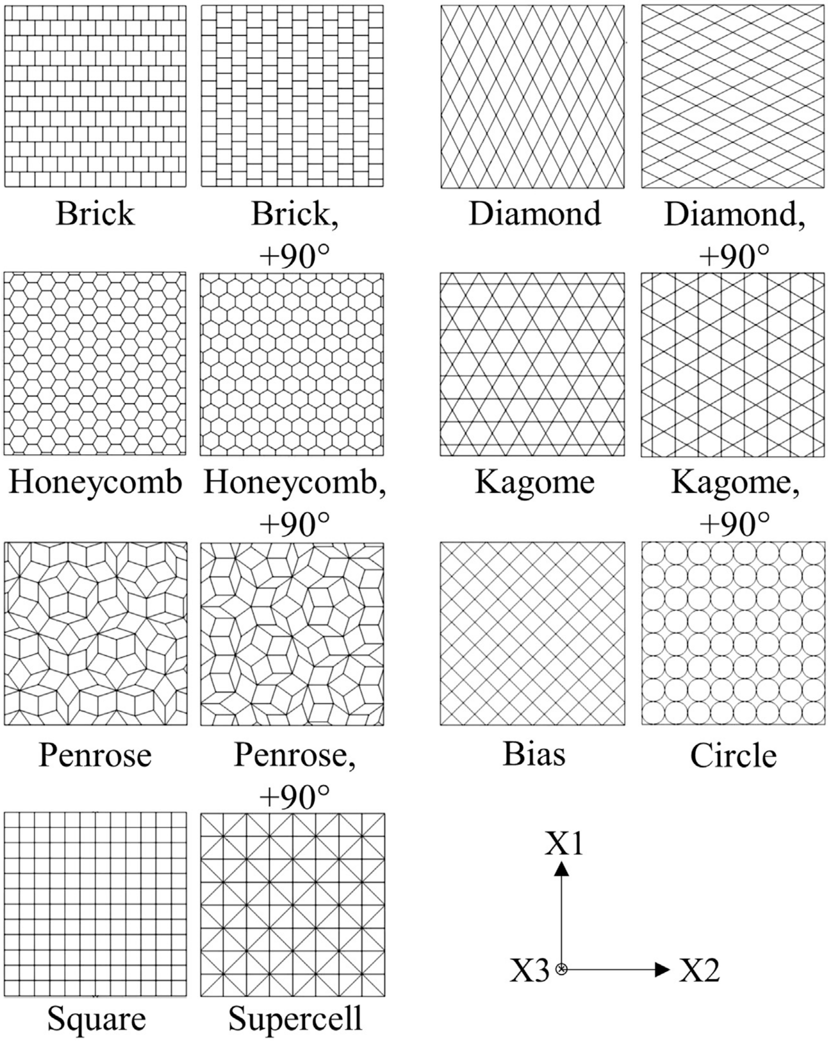

Fig. 1. Overview of numerically investigated profiles.

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