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# Buckling and crush resistance of high-density TRIP-steel and TRIP-matrix composite honeycombs to out-of-plane compressive load

D. Ehinger [a,*], L. Krüger [a], U. Martin [a], C. Weigelt [b], C.G. Aneziris [b]

[a] Institute of Materials Engineering, Technische Universität Bergakademie Freiberg, Germany
[b] Institute of Ceramics, Glass and Construction Materials, Technische Universität Bergakademie Freiberg, Germany

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ABSTRACT

The mechanical and structural responses of high-density TRIP steel and TRIP-steel/zirconia composite honeycomb structures were studied under uniaxial compression in the out-of-plane loading direction over a wide range of strain rates. Their mechanical response, buckling, and failure mechanisms differ considerably from those of conventional thin-walled, low-density cellular structures. Following the linear-elastic regime and the yield limit of the bulk material, the high-density square honeycombs exhibited a uniform increase in compression stress over an extended range of (stable) plastic deformation. This plastic pre-buckling stage with axial crushing of cell walls correlates with the uniaxial compressive response of the bulk specimens tested. The dominating material effects were the pronounced strain hardening of the austenitic steel matrix accompanied by a strain-induced $\alpha$'-martensite nucleation (TRIP effect) and the strengthening effect due to the zirconia particle reinforcement. The onset of critical plastic bifurcation was initiated at high compressive loads governed by local or global cell wall deflections. After exceeding the compressive peak stress (maximum loading limit), the honeycombs underwent either a continuous post-buckling mode with a folding collapse (lower relative density) or a symmetric extensional collapse mode of the entire frame (high relative density). The densification strain and the post-buckling or plateau stress were determined by the energy efficiency method. Apart from relative density, the crush resistance and deformability of the honeycombs were highly influenced by the microstructure and damage evolution in the cell walls as well as the bulk material's strain-rate sensitivity. A significant increase in strain rate against quasi-static loading resulted in a measured enhancement of deformation temperature associated with material softening. As a consequence, the compressive peak stress and the plastic failure strain at the beginning of post-buckling showed an anomaly with respect to strain rate indicated by minimum values under medium loading-rate conditions. The development of the temperature gradient in the stable pre-buckling stage could be predicted well by a known constitutive model for quasi-adiabatic heating.



## 1. Introduction

In recent decades, fundamental topics such as the potential for light-weight applications, crashworthiness, and passive safety have dictated the field of engineering in the civil and military transportation industries. Most of the crash-absorbing concepts applied on front and side bumpers in vehicle bodies or on crash barriers for offshore structures and oil tankers (Alghamdi, 2001) refer to thin-walled, metal-based structures and cellular materials which are able to convert a high degree of kinetic impact energy into plastic deformation energy. Their crush resistance and mode of collapse or failure are significantly influenced by loading direction and impact velocity, as well as by structural and material design.

Pioneering work on the mechanical properties of cellular materials and the prediction of their deformation mechanics is described in the literature (Gent and Thomas, 1963; Patel and Finnie, 1970; Shaw and Sata, 1966). The mechanical response of cellular structures like metal foams or honeycombs is controlled by their relative density $\bar{\rho}$ (the fraction of space occupied by the solid), cell size, and wall thickness as well as by the cell morphology and geometric irregularities (Gibson and Ashby, 1997; Gong and Kyriakides, 2005; Gong et al., 2005; Jang and Kyriakides, 2009a,b). Thus, most open-cell foams and two-dimensional periodic cellular structures with hexagonal, diamond, or square cell shapes that are compressed in-plane obliquely to the longitudinal axis of the cell walls (denoted as the $X_1$ or $X_2$ loading direction) behave as kinematically

* Corresponding author. Tel.: +49 3731 39 2766.
*E-mail address:* David.Ehinger@iww.tu-freiberg.de (D. Ehinger).

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compliant mechanisms or bending-dominated materials (Papka and Kyriakides, 1994; Warren and Kraynik, 1987). After following a nearly linear elastic regime, they develop a maximum loading limit which corresponds to the onset of buckling-type instability (Triantafyllidis and Schraad, 1998). As a consequence, local distortion and rotation of cells is initiated, inducing either uniform cell crushing in a symmetrical and/or an asymmetrical manner or localization of deformation in discrete bands (Klintworth and Stronge, 1988, 1989; Papka and Kyriakides, 1994, 1998a,b; Prakash et al., 1996; Shim and Stronge, 1986). By contrast, the out-of-plane stiffness and strength of honeycombs are much higher because the cell walls undergo a stretch-dominated deformation mode involving large membrane compressions and extensions.

The majority of publications (Foo et al., 2007; Heimbs et al., 2007; Wilbert et al., 2011; Zhang and Ashby, 1992; Zhou and Mayer, 2002) focus on the crush behavior of thin-walled hexagonal aluminum or nomex honeycombs commonly produced by a sheet corrugation or expansion process. Their out-of-plane compressive response is characterized by initial stable elastic deformation of the cell walls before initiating a local flexural buckling at the onset of instability (López Jiménez and Triantafyllidis, 2013). The maximum load indicates the beginning of the folding collapse mode directly followed by intermediate softening of the structure. Further compressive deformation leads to a progressive collapse mechanism with the formation of multiple folds. Similarly to in-plane loading, an extended stress plateau can be observed. The folding process in metallic honeycombs is characterized by extensive plastic bending, rolling, and membrane deformations and is simultaneously accompanied by the localization of deformation in narrow collapse bands (McFarland, 1963; Mohr and Doyoyo, 2003, 2004; Wierzbicki, 1983).

The characterization of strain-rate sensitivity and dynamic crushing response of cellular structures at typical nominal strain rates in the range of $10^2\ \mathrm{s}^{-1} \leqslant \dot{\varepsilon} \leqslant 10^5\ \mathrm{s}^{-1}$ has already been carried out by a large number of research groups using drop weight tower apparatuses (Heimbs et al., 2007; Yamashita and Gotoh, 2005), Hopkinson pressure bar devices (Barnes et al., 2014; Elnasri et al., 2007; Pattofatto et al., 2007; Radford et al., 2007; Reid and Peng, 1997; Tan et al., 2005a,b; Zhao and Gary, 1998), Taylor anvil test fixtures (Baker et al., 1998; Goldsmith and Louie, 1995; Rathbun et al., 2006) and explosive test techniques (Dharmasena et al., 2008; Wadley et al., 2007), often in combination with high-speed photography. Altogether, four basic characteristics indicate the strain-rate sensitivity of cellular structures, including the intrinsic or inherent strain-rate sensitivity of the cell wall matrix material, the increase of pressure because of entrapped fluid in the cells, the inertia effect, and strengthening due to plastic-wave or shock-wave propagation (Gaitanaros and Kyriakides, 2014; Reid and Peng, 1997; Zhao and Abdennadher, 2004; Zhao et al., 2005). Depending on the cell wall matrix material, the cell morphology, the relative density, and the applied impact velocity, a dynamic enhancement of the initial peak load and the plateau stress can occur.

However, the majority of publications mentioned above have one thing in common. Their experimental and numerical investigations were focused on low-density cellular structures with relative densities of between 0.02 and 0.1. Hence, a limited amount of literature has been published that deals with the out-of-plane compressive behavior of high-density metallic honeycombs (Baker et al., 1998; Côté et al., 2004, 2006; Lu and Hinnerichs, 2001; Radford et al., 2007; Wadley et al., 2007; Wang et al., 2005). These research groups have already shown that prismatic or corrugated high-density honeycombs (relative density $\bar{\rho} > 0.1$) made from high-strength metal alloys or high strain-hardening stainless steels are promising for applications in automobile crash absorbers, in blast-resistant sandwich plates for shock mitigation, or as armor materials for personnel carriers. In high-density metallic honeycombs, plastic cell wall buckling and plastic yielding near the cell nodes and edges are the dominant deformation mechanisms before the beginning of post-buckling collapse.

With regard to the present study, the cell wall matrix material of the square honeycombs consisted of high-alloyed austenitic AISI 304 CrNi steel with or without reinforcement by zirconia particles partially stabilized by MgO (Mg-PSZ). The increase in strength due to the strain-induced α'-martensite formation in the steel matrix (viz. the Transformation Induced Plasticity, or 'TRIP' effect) and the deformation constraints imposed by the embedded ceramic particles make important contributions to the honeycomb's crush resistance and energy absorption capability (Aneziris et al., 2009; Ehinger et al., 2012a, 2011, 2012b; Krüger et al., 2010).

This research work focuses on the stress–strain behavior of these square TRIP steel and TRIP-matrix composite honeycombs under out-of-plane (OOP) compression over a wide range of strain rates. Of particular interest is the buckling and post-buckling behavior that governs their strength and energy absorption. Two honeycombs of different relative densities were investigated. Their compressive stress–strain responses were correlated with the uniaxial response of the bulk material processed in the same manner using the same powder feedstock. In this regard, the influences of strain rate and Mg-PSZ content (0, 5 and 10 vol.%) on the mechanical properties and deformation mechanisms were considered. Infrared thermography was used during the compression experiments to enable in situ recording of failure and temperature. The temperature evolution was further described by a modified constitutive model for quasi-adiabatic heating (Meyer et al., 2007).

## 2. Material and methods

The honeycombs presented were fabricated by a modified ceramic extrusion technology which, unlike the common sheet corrugation, expansion, and slotting techniques, provides higher design flexibility and does not require additional joining processes (Baker et al., 1998; Côté et al., 2004, 2006). The powder feedstock consisted of an austenitic AISI 304 CrNi steel with different particle fractions of Mg-PSZ. It was processed to a plastic paste using certain powder mixing and blending steps (Weigelt et al., 2011). After plastic molding in a de-airing single-screw extruder with vacuum chamber, successive drying and debindering processes followed. The final pressure-less sintering was carried out at 1350 °C for 2 h in a 99.999% argon atmosphere.

The experimental test series were performed on sintered bulk materials and square honeycombs made from pure TRIP steel (denoted as 0Z, Fig. 1a) and two TRIP-matrix composite materials consisting of 5 and 10 vol.% zirconia (5Z or 10Z, Fig. 1b). Their chemical data with regard to the compositions of the sintered TRIP-steel matrices and the Mg-PSZ ceramic powder are given in Tables 1 and 2, respectively.

Two regular square honeycombs (cubed specimen, edge length of 8 mm) with an in-plane array of $4 \times 4$ (viz. 196 cells per square inch) and $2 \times 2$ closed cells (64 cpsi) denoted by a different average wall thickness and cell size were deformed under quasi-static compression in the out-of-plane loading direction $X_3$ (Fig. 2a). Additionally, the former higher-density honeycomb structure was subjected to compressive loads at various strain rates in the range of $10^{-3} \leqslant \dot{\varepsilon} \leqslant 1.9 \times 10^3\ \mathrm{s}^{-1}$. Except for the dynamic impact tests in a Split-Hopkinson Pressure Bar (SHPB), larger specimens with a cross-section of $14 \times 14$ square cells (196 cpsi) and retained outer skin were used (Fig. 2b). These specimens ensured an accurate temperature measurement during deformation at medium strain rates. A further honeycomb geometry with $8 \times 8$ cells (64 cpsi)