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Compressive behaviour of unconstrained and constrained integral-skin closed-cell aluminium foam

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ABSTRACT

The aim of this paper is to evaluate the quasi-static and dynamic compressive crush performance of integral-skin closed-cell aluminium alloy foam with and without radial constraints. The foam specimens were prepared by the powder compact foaming method. The behaviour under different loading conditions (loading velocity and radial constraints) has been determined by an extensive experimental program. The results show a significant increase in the collapse stress of the integral-skin closed-cell aluminium foam under quasi-static loading when radial constraints are applied. The radial constraint induces a significant strain hardening of the foam, where the densification occurs at lower strains, consequently enhancing the energy absorption per unit volume of the deformed foam. The strain hardening is also sensitive to the foam density, increasing with the density.

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1. Introduction

Lightweight aluminium alloy closed-cell foams are an important class of cellular materials for structural applications [1]. They are usually used as a core of sandwich panels [2] or a filler [3] of hollow structures (e.g. empty tubes) for several multi-functional construction elements in vehicles as crash energy absorption, sound absorption and vibration damping structures. In these practical engineering applications, especially when the foam is used to fill hollow structures (e.g. empty profiles of the chassis), the deformation of the foam occurs under constrained stress conditions. These hollow structures will act as a barrier for unconstrained transversal displacements. The description of the response of the metal foams under constraint loading conditions is essential for designing new foam filled components. Nonetheless, these studies are still limited [4–8]. Most of the studies have been performed using uniaxial compression tests under quasi-static and dynamic loading conditions, where the foam is compressed without any radial constraints [3,9–11]. Some studies have been also carried out on the evaluation of compressive [12,13] and bending [14,15] performance under quasi-static and dynamic loading conditions of the lightweight foam filled tubes (FFTs), understanding the deformation and failure of the foams placed inside the empty tubes. Recently, *ex situ* FFTs [12,14] and *in situ* FFTs [13,15] were developed and manufactured using the powder compacting foaming (PCF) method by inserting the preformed aluminium alloy integral-skin foam filler into an empty aluminium alloy tube and/or by filling the aluminium alloy empty tube with aluminium alloy foam during its formation, respectively. The results have demonstrated an improved compressive and bending performance of the FFTs, where the *in situ* FFTs demonstrated a more stable and predictable mechanical performance under axial compressive [13] and bending loads [15]. The results have shown that the mechanical response of such FFTs is affected by the interaction between the foam and the tube wall. A good interface bonding between the foam core and the tube is a pre-requisite for a better mechanical response of the composite structure [13]. Furthermore, the deformation mode and response of these FFTs seem to be a combination of the responses of the individual components (integral-skin foams and empty tubes). The crushing stresses of the *in situ* FFTs and *ex situ* FFTs is equal or exceeds the sum of the individual responses of the integral-skin foam and the empty tube, respectively. For example, in the case of *ex situ* FFTs the gap between the foam filler and the outer tube disappears during the loading, resulting in a contact between the interfaces [15]. Consequently, higher stresses (stiffness) can be observed for the *ex situ* FFTs due to the interaction including friction between the tube and the foam filler and constrained radial deformation of the foam filler by the outer tube. Nonetheless, all of these studies are not

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able to evaluate separately the effect of the constraints on the metal foam due to the fact that the deformation of the foam occurs simultaneously with the deformation of the body constraint (empty tube). In fact, it would have required separate studies for elucidating such detailed mechanisms. Strain hardening is not only important for the structural integrity of components that is limited by extreme plastic deformation, but also plays an important role in controlling the onset of damage. Studies on the experimental methods for achieving dynamic multi-axial loading which is closer to the actual working conditions for energy absorbing purposes are almost unpublished. With additional constrained testing it is also possible to define the material properties for the constitutive models used in various engineering computer codes more accurately. For example, the hydrostatic pressure is an important mechanical parameter to develop computational models to predict the mechanical behaviour of these materials. Therefore, this paper presents the results of a comprehensive experimental testing programme on the unconstrained and constrained compression response of the integral-skin closed-cell aluminium alloy foam under quasi-static and dynamic loading, exploring their deformation and failure mechanisms.

Table 1
Physical properties of the integral-skin Aluminium alloy foams.

Specimen number	Physical properties				Loading velocity (mm/s)
	Diameter (mm)	Height (mm)	Mass (g)	Density (g/cm^3)	
Unconstrained foams					
#1	28	29	11.85	0.66	0.1
#2			14.00	0.78	
#3			14.35	0.80	
#4	28	29	11.78	0.66	284
#5			12.86	0.72	
#6			13.85	0.78	
Constrained foams					
#7	28	29	13.34	0.75	0.1
#8			12.99	0.73	
#9			13.54	0.76	
#10	28	29	12.64	0.71	284
#11			12.43	0.70	
#12			12.3	0.69	
#13			12.56	0.70	

2. Materials and experimental methods

2.1. Preparation of the specimens

Cylindrical specimens of integral-skin aluminium alloy foams (28 mm in diameter and 29 mm in length) were prepared using an experimental methodology based on PCF method [16]. A cylindrical closed steel mould (mould cavity diameter: 28 mm, mould cavity length: 29 mm) was used to prepare the cylindrical specimens of integral-skin foams (Fig. 1). They were fabricated by heating the steel mould containing foamable precursor material made of aluminium, silicon (7 wt.%) and titanium hydride (0.5 wt.%) in a pre-heated furnace at 700 °C. Table 1 lists the main physical properties of the specimens.

2.2. Mechanical characterisation

The cylindrical specimens were subjected to uniaxial compression tests under quasi-static and dynamic loading conditions using a servo-hydraulic dynamic INSTRON 8801 testing machine. The cross-head rates were 0.1 mm/s (quasi-static) and 284 mm/s (dynamic). The uniaxial compression tests of integral-skin Al-alloy foam specimens were performed using two different boundary set-ups (Fig. 2): (1) standard uniaxial compressive loading without radial constraints (free lateral displacements, Fig. 2a) and (2) compressive loading with radial constraints (constrained lateral displacements, Fig. 2b). The standard compressive tests were performed according to the ISO 13314: 2011 [17] by simply placing the foam specimen between parallel rigid plates of the universal testing machine. The compressive tests with radial constraints (constrained boundaries) were performed by placing the foam specimens into a cylindrical steel die (made of steel St37-2) having an inner diameter of 30 mm and 40 mm in height. The inner area of the closed die was chosen in such a way that all specimens could be fitted into the closed die easily. The diameter of the aluminium foam specimens was approximately 0.1–0.2 mm smaller than the inner diameter of the test die. Testing in a closed die almost completely inhibits transverse displacements which is more comparable to applications, where the foam is used as core in shell structures. This minimum space for transverse displacements should be taken into account when interpreting test results from constrained compression tests. In all constrained compression tests, the inner die and punch surfaces were coated with high pressure resistant silicone based lubricant. Remaining forces from friction between the specimen and die, as well as between the punch and die, affect the experimental measurements and cannot be determined.

The load-displacement data were converted to engineering stress-strain data, according to the initial specimen's dimensions. The absorbed energy per unit volume (strain energy density) curve for each type of the structure was calculated by integrating the stress-strain curves. The deformation and failure modes under unconstrained quasi-static loading were captured using a standard high-definition video camera and at dynamic loading an infrared thermal camera. Infrared thermography is used as a tool to trace plastification zones and overall yielding process scenario, thus enabling full field visualization of deformation process. Infrared thermography based on fast cooled InSb middle wave detectors enables acquiring clear images at frequencies up to approximately 700 Hz. After elastic loading, yielding is characterized by significant heat generation. As shown in [18] thermal field is equivalent to Von Mises strain distribution. Zones with higher strains are

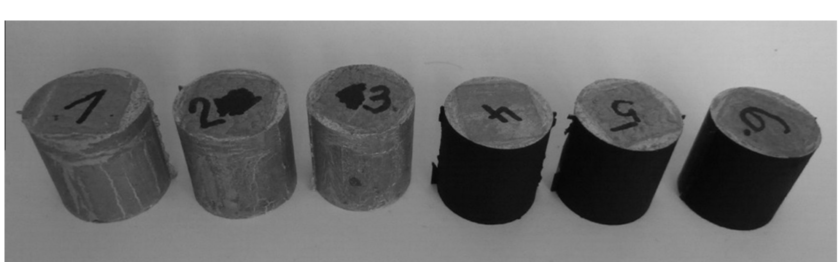

Fig. 1. Cylindrical specimens of integral-skin aluminium alloy foams.

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