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Shear behavior of aluminum lattice truss sandwich panel structures

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Abstract

Age hardenable 6061 aluminum tetrahedral lattice truss core sandwich panels have been fabricated by folding perforated sheets to form highly flexible cellular cores. Flat or curved sandwich panels can be fabricated by furnace brazing the cores to facesheets. Flat sandwich panels with core relative densities between 2 and 10% have been fabricated and tested in the $\sigma_{\pm 13}$ shear orientation (minimum shear strength orientation for a tetrahedral lattice) in the fully annealed (O) and aged (T6) conditions. The shear strength of the lattices increased with relative density, parent alloy yield strength and work hardening rate. Analytical stiffness and strength predictions agree well with measured values for all relative densities and parent alloy heat treatments investigated. The stiffness and strength of 6061-T6 aluminum tetrahedral lattice structures are shown to be comparable to those of conventional 5052-H38 aluminum closed cell hexagonal honeycombs and more than 40% stiffer and stronger than flexible honeycombs used for the cores of curved sandwich panels.

Keywords: Lattice structures; Sandwich structures; Aluminum alloys; Brazing

1. Introduction

Millimeter cell size, aluminum alloy lattice structures with various open cell topologies are attracting interest as lightweight core structures for sandwich panel constructions. For bending dominated applications of sandwich panels; the facesheets carry the bending stresses with one facesheet in compression and one in tension and the flexural strength of the panel is governed by the shear response of the core and by the strength of its attachment points (nodes) to the facesheets. The core also increases the flexural stiffness of the panel by providing a separation between the two facesheets.

Lattices appear to be mechanically competitive alternatives to prismatic (corrugated) and perhaps honeycomb structures when configured as the core of a sandwich panel. These lattice sandwich structures are of particular current interest because of their potential fully open interior structure which facilitates multifunctional applications [1–4]. For example, lattice core sandwich panels appear capable of supporting significant structural loads while also facilitating cross flow heat exchange [5–8]. Some structures also enable high authority shape morphing [9–14] and all appear to provide significant high intensity dynamic load protection [15–21]. Lattices are also flexible and are amenable to the creation of singly or compound curved sandwich panels. They may also alleviate some of the delamination and corrosion concerns associated with the use of traditional closed cell honeycomb sandwich panels [22,23].

The emergence of microscale lattice truss structures originally envisioned at the meter scale by Buckminster Fuller [24] has been paced by the development of practical methods for their manufacture [4,25]. Initial efforts to fabricate millimeter scale structures employed investment casting of high fluidity casting alloys such as copper/beryllium [26], aluminum/silicon [27–30] and silicon brass [27]. However, the tortuosity of the lattices and ensuing casting porosity made it difficult to fabricate high quality structures at low relative densities (2–10%) identified as optimal for sandwich panel constructions [31]. While some lattice constructions appear to possess significant tolerance to defects such as occasional weak trusses or nodes [32,33], the low toughness of the materials used to make these as-cast lattice materials have often lacked the mechanical robustness required for the most demanding structural applications [34].

Efforts to exploit the inherent toughness of many wrought engineering alloys led to the development of alternative lattice fabrication approaches based upon perforated metal sheet folding [35]. These folded truss structures can be bonded to each

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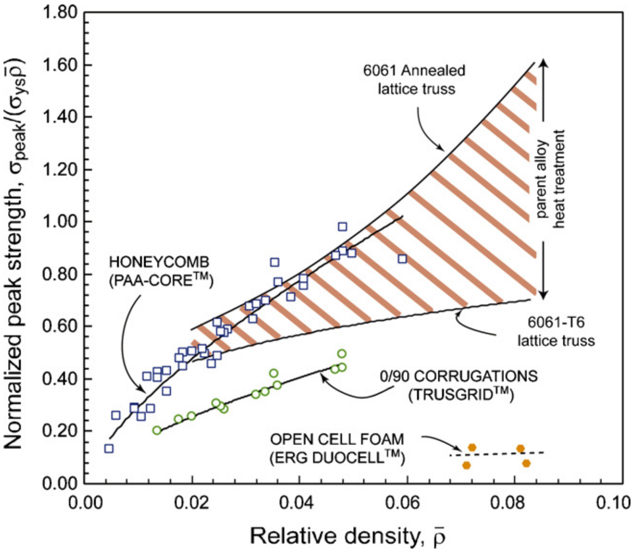

Fig. 1. Comparison between the normalized compressive peak strengths of the aluminum tetrahedral lattice structures and commercially available competing topologies that utilize aluminum alloys [42].

other or to facesheets by conventional joining techniques such as brazing, transient liquid phase (TLP) bonding or welding techniques to form all metallic lattice truss sandwich panels. Panels fabricated from austenitic stainless steels with tetrahedral [35–37] and pyramidal lattice truss [38–41] topologies have been made by node row folding of a patterned sheet to form the core and TLP bonding to facesheets. Because of the high temperatures normally encountered with TLP bonding, this process results in sandwich panels which remain in a low strength, annealed condition. While these structures appear much more robust than their investment cast counterparts, the reduced strength of their annealed microstructure can limit their potential uses for some structural applications.

The perforated sheet folding method has recently been extended to age hardenable aluminium alloys such as the 6061 system, and tetrahedral lattices made from this alloy have been shown to exhibit high specific compressive strengths (Fig. 1) [42]. Comparisons with other cellular aluminum topologies (Fig. 1), confirm that 6061 aluminum alloy tetrahedral lattice structures are far superior to aluminum open cell metal foams and prismatic corrugations. The compressive response of the tetrahedral lattice was comparable to that of honeycomb panels of similar specific mass and found to be sensitive to the lattices heat treatment condition. Annealed cores with high tangent moduli were more efficient than age hardened structures and significantly exceeded elastic-ideally plastic strength predictions. Inelastic column-buckling models robustly predict the through thickness compressive strengths and resolved the important role of the parent materials post-yield tangent modulus in delaying the onset of unstable inelastic buckling.

Here, we explore the in-plane shear stiffness and strength of these 6061 aluminum tetrahedral lattice structures described above. The measured shear stiffness and strengths of the lattice truss structures are compared to analytical predictions and shown to be comparable to those of other topologies for aluminum based sandwich structures.

2. Fabrication methodology

2.1. Tetrahedral lattice truss fabrication

A detailed description of the fabrication approach for making 6061 aluminum alloy lattice truss structures can be found in Kooistra et al. [42]. Briefly, a folding process was used to bend elongated hexagonal perforated 6061 sheet to create a single layer tetrahedral truss lattice. The folding was accomplished using a paired punch and die tool to fold node rows into regular tetrahedrons with three trusses emanating from each node resulting in a highly flexible core structure.

The unit cell of a tetrahedral lattice is shown in Fig. 2. The relative density, $\bar{\rho}$, of a tetrahedral lattice with 50% occupancy of the available tetrahedral sites is given by ref. [27]:

$$\bar{\rho} = \frac{2}{\sqrt{3}} \frac{1}{\cos^2\omega \sin\omega} \left(\frac{t}{l}\right)^2 \quad (1)$$

where ω is the angle between the truss members and the tetrahedron base plane ($\omega = 54.7°$ for regular tetrahedrons) and t and l are the sheet thickness and truss member length, respectively. The relative density of the lattice was varied here by modification of the sheet thickness and the perforation dimensions to maintain a square truss cross section and a constant truss length (Table 1).

2.2. Sandwich panel fabrication

Sandwich panels were constructed from the folded lattice structures by placing them between 6951 aluminum alloy face sheets clad with a 4343 aluminum–silicon braze alloy. The

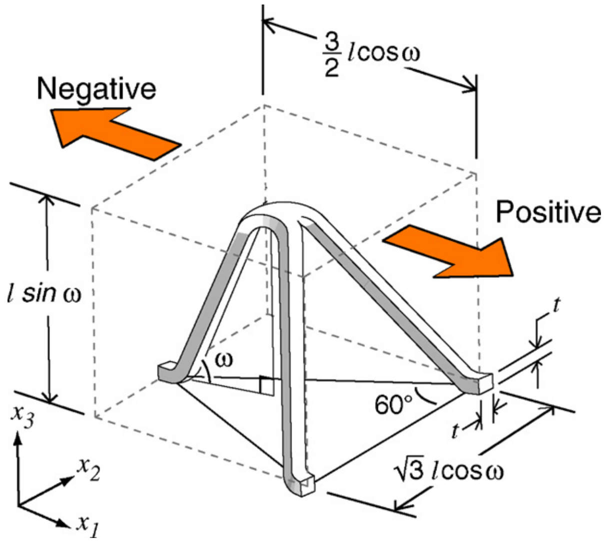

Fig. 2. Tetrahedral unit cell used to derive relative density and mechanical properties. The positive and negative shear directions are also shown. They result in different stress–strain behaviors because of the different truss tensile stretching and compressive buckling configurations.