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Mechanical properties of an extruded pyramidal lattice truss sandwich structure

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Metallic sandwich structures with lattice topology cellular cores are being developed for weight-sensitive applications. A combination of extrusion and electrodischarge machining has been used to fabricate pyramidal lattice sandwich structures from 6061 aluminum, where the nodes have identical properties to those of the trusses/facesheets. Inelastic buckling dictated the compressive behavior, whereas tensile fracture of the extensionally strained trusses governed the shear response. No nodal failure modes were observed and the compression and shear properties agree well with predictions of micromechanical models.

Keywords: 6061; Lattice truss structure; Cellular material

Lightweight sandwich panel structures consisting of low-density cores and solid facesheets are widely used in engineering applications [1]. Cellular core structures based upon honeycomb topologies are often used because of their high compressive strength-to-weight ratios and high bending stiffness [2]. These honeycomb structures are closed-cell with limited access into the core region. The cores may be attached to the facesheets by conventional joining methods such as adhesive bonding, brazing, diffusion bonding and welding. Recently, lattice truss structures have been explored as an alternative cellular core topology [3–6]. Pyramidal lattice truss structures are usually fabricated from high-ductility alloys by folding a perforated metal sheet along node rows. Conventional joining methods such as brazing or laser welding are then used to bond the core to solid facesheets to form a sandwich structure. The lattice topology, core relative density and parent alloy mechanical properties determine the mode of truss deformation and therefore the out-of-plane and in-plane mechanical properties of these structures.

The design of the core–facesheet node interface is of the utmost importance. Ultimately, this dictates the maximum load that can be transferred from the facesheets to the core. Node bond failure has been identified as a failure mode for sandwich structures, especially metallic honeycombs [1]. However, analogous node failure modes have been observed in sandwich panels utilizing tetragonal and pyramidal lattice truss cores during shear loading [7,8]. When sandwich panels are subjected to intense shear or bending loads, the node transfers forces from the facesheets to the core members (assuming adequate node bond strength and ductility exists) and the topology for a given core relative density dictates the load carrying capacity. When the node–facesheet interfacial strength is compromised by poor joint design or inadequate bonding methods, node bond failure occurs, resulting in premature failure of the sandwich panel. Numerous factors determine the robustness of nodes, including joint composition, microstructure, degree of porosity, geometric effects (which control stress concentrations) and the node contact area.

Micromechanical models for the stiffness and strength of pyramidal lattice truss cores, comprising elastic–plastic struts with perfect nodes, have been recently developed [8,9]. These models assumed that the trusses are connected to rigid facesheets and are of sufficiently low aspect ratio that bending effects make a negligible contribution to the stiffness and strength. These micromechanical models also assume the node strength is the same as the strength of the parent metal alloy. However, the measured elastic moduli rarely

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reach the predicted values for reasons that have not been fully elucidated [7,10].

Here, an extrusion and electrodischarge machining (EDM) method has been developed to fabricate a pyramidal lattice core sandwich structure. The approach is readily extendable to tetrahedral and to multilayer versions of these lattices. In this approach, a 6061 aluminum alloy corrugated core sandwich panel is first extruded with integral core and face sheets. The corrugated core is then penetrated by an alternating pattern of triangular-shaped EDM electrodes normal to the extrusion direction to form the pyramidal lattice. The process results in a sandwich panel in which the core–facesheet nodes possess the parent alloys' metallurgical and mechanical properties. The out-of-plane compression and in-plane shear mechanical properties of the structure have been measured and found to be very well predicted by analytical estimates.

A 6061 aluminum alloy was extruded with a regular prismatic structure using a 17.8 cm diameter, 300 ton direct extrusion press at 482 °C (Fig. 1). After this extrusion step, the resulting corrugated core sandwich panel structures had a web thickness of 3.2 mm, a core height of 19.1 mm, 5.2 mm thick facesheets and a web inclination angle of 60°. The relative density of the corrugated core was 25%. The extruded panels were solutionized, water quenched and heat treated to a T6 condition. An alternating pattern of triangular-shaped EDM electrodes were then inserted normal to the extrusion direction to form the pyramidal lattice sandwich panel (Fig. 2). The process resulted in a sandwich panel in which the core–facesheet nodes had identical microstructure, composition and mechanical properties to those of the trusses and facesheets. Figure 3 shows a photograph of one of the pyramidal lattice sandwich structures. It is 4 unit cells wide by 4 unit cells long and was used for compression measurements. The shear response was measured using samples (not shown) that were 4 unit cells wide and 10 unit cells long.

The relative density can be derived for the pyramidal structure depends upon the truss cross-sectional area, t^2, its inclination angle, ω, and length, l [9]. The ratio of the metal volume in a unit cell to that of the unit cell then gives the relative density

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

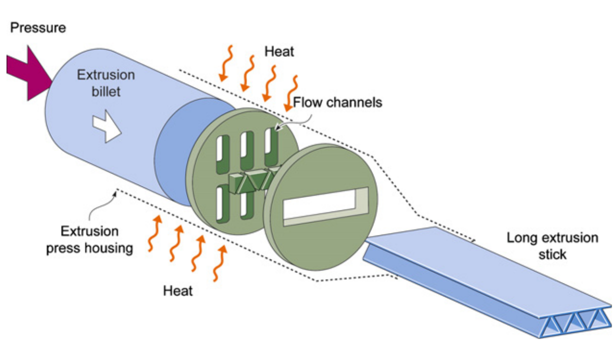

Figure 1. Schematic illustration of the extrusion process used to produce 6061 aluminum corrugated sandwich structures.

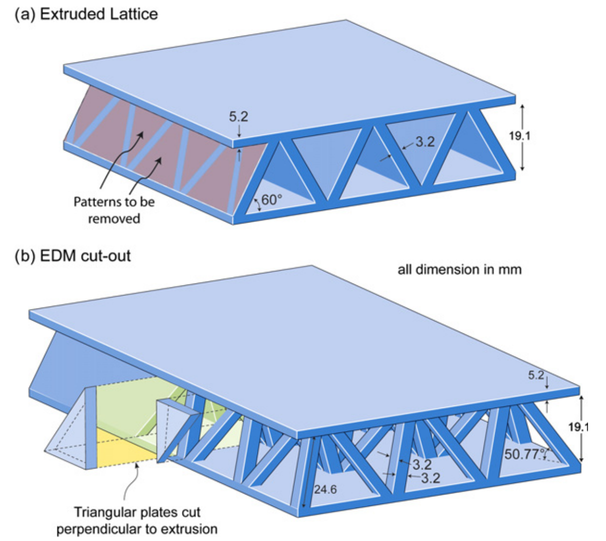

Figure 2. Schematic illustration of the regions in the corrugated core that are removed by electrodischarge machining to create a pyramidal lattice core sandwich panel structure.

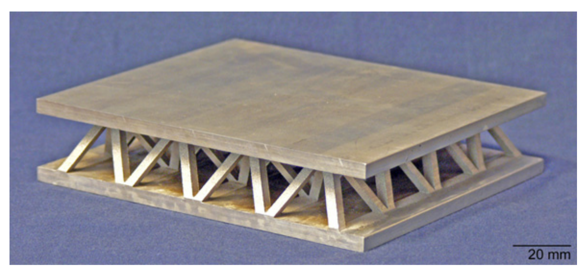

Figure 3. Photograph of an extruded/electrodischarge-machined pyramidal lattice sandwich structure. The core relative density is 6.2%.

For the samples manufactured here, $t = 3.2$ mm, $l = 24.6$ mm and $\omega = 50.77°$, resulting in a predicted relative density of 6.5%. The experimentally measured relative density was $6.2 \pm 0.01\%$.

The lattice truss structures were tested at ambient temperature in compression and shear at a nominal strain rate of 10^{-2} s^{-1} in accordance with ASTM C365 and C273 using a compression shear plate configuration [11,12]. A laser extensometer measured the compressive strain by monitoring the displacements of the unconstrained facesheets with a displacement precision of ± 0.001 mm. The shear strain was obtained by monitoring the displacements of the shear plates with a measurement precision of ± 0.010 mm.

The through thickness compressive stress–strain response is shown in Figure 4. Following an initial linear response, a peak was observed in the compressive stress that coincided with initiation of the buckling of the lattice truss members and the formation of a plastic hinge near the center of the truss members. Continued loading resulted in core softening up to an engineering strain of $\sim$0.25, at which point the load-carrying capacity increased rapidly as the deformed trusses made contact with the facesheets. During the core-softening phase, small fractures were observed to form on the tensile

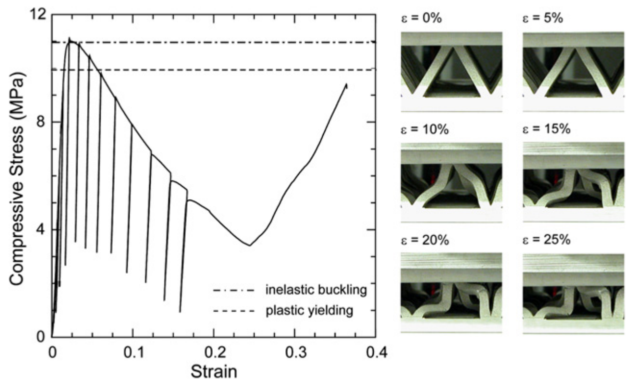

Figure 4. Compressive stress vs. strain response and photographs of the lattice deformation at strain levels of 0%, 5%, 10%, 15%, 20% and 25%. Predictions of the stress for inelastic buckling and plastic yielding of the trusses are also shown.

stressed side of the trusses. These were first seen at strains of between 0.10 and 0.12. No failures at the truss–facesheet nodes were observed during any of the tests.

The in-plane shear stress–strain response is shown in Figure 5. In this test orientation, each unit cell had two truss members loaded in compression and two in tension. The sample exhibited characteristics typical of lattice truss-based sandwich cores including: elastic behavior during initial loading and increasing load support capability until the peak strength was reached. Continued loading continued at a constant stress up to a strain of ~0.13, at which point the sample failed by fracture of the tensile loaded lattice members near their midpoint. Some plastic buckling was observed on truss members at the ends of the sandwich panel. It is a manifestation of the compressive loading component of the ASTM 273 test method. No evidence of node failure was observed during any of the shear experiments.

Tensile coupons of the aluminum 6061 alloy were used to determine the mechanical properties of the parent aluminum alloy. Tensile tests were performed according to ASTM E8 at a strain rate of 10^{-3} s^{-1} [13]. The average Young's modulus, E_s, and 0.2% offset

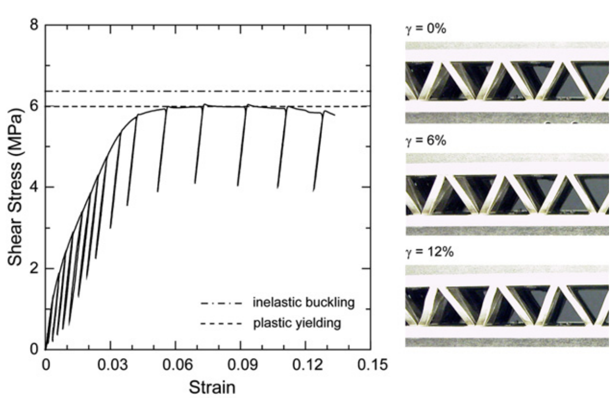

Figure 5. Shear stress vs. shear strain response and photographs of the lattice deformation at strain levels of 0%, 6% and 12%. Predictions of the stress for inelastic buckling and plastic yielding of the trusses are also shown.

Table 1. Analytical expressions for the compression and shear stiffness and strength of a pyramidal lattice truss core sandwich structure [8,9]

Mechanical property	Analytical expression
Compressive stiffness	$E_c = E_s \cdot \sin^4 \omega \cdot \bar{\rho}$
Compressive strength (plastic yielding)	$\sigma_{pk} = \sigma_{ys} \cdot \sin^2 \omega \cdot \bar{\rho}$
Compressive strength (inelastic buckling)	$\sigma_{pk} = \sigma_{cr} \cdot \sin^2 \omega \cdot \bar{\rho}$
Shear stiffness	$G_c = \frac{1}{8} E_s \cdot \sin^2 2\omega \cdot \bar{\rho}$
Shear strength (plastic yielding)	$\tau_{pk} = \frac{1}{2\sqrt{2}} \sigma_{ys} \cdot \sin 2\omega \cdot \bar{\rho}$
Shear strength (inelastic buckling)	$\tau_{pk} = \frac{1}{2\sqrt{2}} \sigma_{cr} \sin 2\omega \cdot \bar{\rho}$

yield strength, σ_{ys}, were 69 GPa and 268 MPa, respectively. The tangent modulus, E_t, at the inelastic bifurcation stress was 282 MPa.

The peak strength of a lattice truss core is determined by the mechanism of strut failure, which depends on the cell geometry, strut material properties and the mode of failure loading. Table 1 summarizes the micromechanical predictions for the pyramidal lattice [8,9]. The micromechanical predictions for the compressive and shear peak strength are shown in Figures 4 and 5 for truss members that fail by plastic yielding or inelastic buckling. There is excellent agreement between the analytical model predictions of the peak strengths consistent with the observed modes of deformation.

The compression and shear stiffness's were measured from periodic unload/reload measurements. Figure 6 shows the non-dimensional compressive stiffness, $\Pi = E_c/(E_s\bar{\rho})$, vs. compressive strain (here E_c and E_s are the Young's moduli of the core and the solid parent alloy, respectively). The predicted non-dimensional compressive stiffness is 0.36. The experimental data fall slightly above 0.36 just prior to attainment of the peak strength and then decrease during the inelastic buckling phase of deformation. Some minor anomalies were observed in the linear elastic regions corresponding to run-out which can be seen in the compressive stress–strain response. Figure 6 shows the non-dimensional shear stiffness, $\Gamma = G_c/(E_s\bar{\rho})$, vs. shear strain (here G_c is the shear stiffness of the core). The predicted non-dimensional shear stiffness is 0.12 and the experimental data are in excellent agreement with this up to failure of the panel.

A new method for fabricating a lattice truss core sandwich panel structure has been developed using a combination of extrusion and EDM. The approach has been illustrated by the fabrication and mechanical property evaluation of sandwich panels made from a 6061 aluminum alloy; however, the method appears applicable to any alloy system that can be easily extruded. For materials that cannot be extruded, the EDM method could be performed in two orthogonal directions (instead of one as described here) on a monolithic plate resulting in a similar lattice structure. The approach therefore appears extendable to most conductive material systems.

The measured peak compressive and shear strengths were found to be in excellent agreement with the micromechanical model predictions for the operative truss member failure mechanisms, inelastic buckling for compression and plastic yielding (followed by tensile

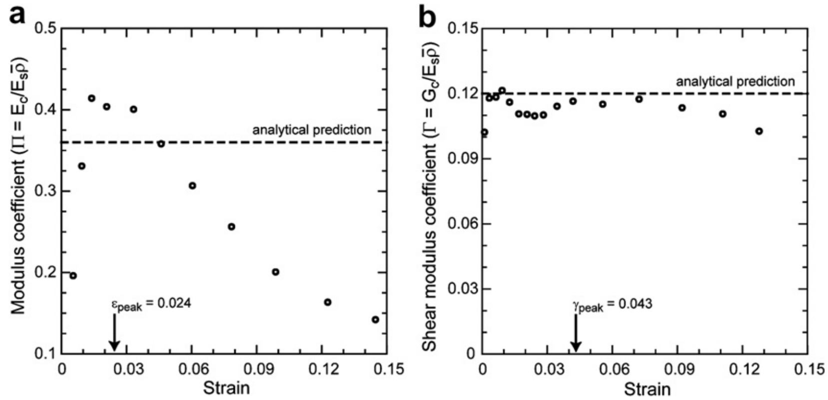

Figure 6. The normalized (a) compression and (b) shear stiffness measurements vs. strain.

fracture) for shear. The non-dimensional compression and shear moduli coefficients were found to be in excellent agreement with the analytical predictions.

Most sandwich panel structures suffer from node failure during static and dynamic testing [8,14–18]. These failures are initiated at defects or in weak or embrittled regions that result from the panel-to-core bonding process. The fabrication method described above results in sandwich panels in which the core–facesheet nodes have identical properties to those of the trusses and facesheets. Secondary joining methods such as brazing or welding have been eliminated with this process. No evidence of nodal failure was observed during compression or shear loading of the samples fabricated by the method described here.

The method of sandwich panel manufacture described here has been used to fabricate sandwich panels that eliminate the incidence of nodal failures and the panels mechanical properties are found to be governed only by the geometry of the sandwich panel, the alloy constituent mechanical properties and the mode of loading. These properties are well predicted by recent micromechanical models.

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