Wrought Aluminum Truss Core Sandwich Structures

DAVID J. SYPECK

Wrought metallic sandwich structures with open cell truss cores are a relatively new class of multifunctional material systems that can be made using affordable deformation, assembly, and joining processes. Here, the design and fabrication of these types of structures from wrought, heat-treatable aluminum alloys is reported. Tetrahedral truss cores were made by bending perforated aluminum alloy sheets. Plain square weave truss cores were made by stacking and aligning precrimped aluminum alloy weaves. Both core types were metallurgically bonded between braze clad aluminum alloy facesheets using a vacuum brazing approach. With this method, affordable truss core sandwich structures can be made from a variety of wrought aluminum and other alloys. Design methodology and multifunctional applications are discussed.

I. INTRODUCTION

COMPACT, lightweight structures that support loads in an efficient and cost-effective way are valued for many applications.[1] Recent progress in the design, fabrication, and performance of sandwich structures with open cell truss cores[2–7] suggests an alternative to honeycomb core designs. These new structures have mechanical properties that compare favorably to honeycomb core structures but with added multifunctional possibilities (*e.g.*, cross-flow heat exchange, fuel storage space, conduits for wiring and piping, *etc.*) owing to the open, accessible space within the core.[8,9] Figure 1 illustrates an example involving load support with active cooling. This structure could be categorized as a synthetic multifunctional material system in the sense that it supports mechanical loads while also performing an additional function.[10] The open cell structures may also be less susceptible to internal corrosion and depressurization induced delamination. Furthermore, many of them appear to be more easily formed into complex curved shapes than conventional honeycombs (which exhibit anticlastic curvature upon bending[11]).

Past approaches to fabricating miniature truss core sandwich structures from Al alloys have involved an investment casting route.[2,3,12] Like many casting alloys, strength knockdown due to casting defects and low alloy ductility have been observed. With casting, there are also limits to the types of materials that can be used (*e.g.*, high fluidity needed for intricate shapes), the range of obtainable properties (relative to wrought metals), and whether they respond to postprocessing (*e.g.*, heat treatment). Furthermore, the facesheets of cast sandwich structures tend to be thicker than desired, surface finishes can be rough (*e.g.*, notch sensitive), and fabrication costs are comparatively high. For lightweight structural applications, wrought metals are normally used.

Miniature truss core sandwich structures have been fabricated from wrought Ni, Fe, Cu, and Ti alloys by vacuum or inert gas brazing processes.[5,7,13] Figures 2 and 3 show the quasi-static crushing behavior for a woven core sample made in this fashion. Owing to the appreciable ductility of the wrought Fe alloy, its bonding agent, and the open space within the core, large amounts of mechanical energy were absorbed. If structures of this type were made from wrought Al alloys, significant weight savings could be achieved with other potential benefits (*e.g.*, high base metal conductivity). Such property motivations suggest a need to design and fabricate from lighter weight, but more difficult to braze wrought Al alloys. Here, this is demonstrated in a straightforward and affordable fashion, which overcomes many deficiencies of the prior art. Design methodology and multifunctional applications are discussed.

II. CORE DESIGN

The mechanical performance characteristics of truss core sandwich structures with tetrahedral, plain square weave, and other stretching/compressing dominated open cell architectures have been addressed in prior studies.[1–8] Here, simple relations that guide core fabrication are revisited.

A. *Tetrahedral Truss Core*

Consider a sandwich structure core made up from a sheet of tetrahedral units with leg members of length l and square cross-section dimension h (Figure 4). The angle each member makes with a line extending from the center of a triad base to its peak is acos $(\sqrt{2/3})$, the angle between members is acos (1/2), the triad height is about $l(\sqrt{2/3})$, and it provides support over a planar area $\sqrt{3}l^2/2$. The relative density of the tetrahedral core is close to[7]

$$\frac{\rho_c}{\rho_s} = \frac{3\sqrt{2}h^2}{l^2} \qquad [1]$$

where ρ_s is the base material density.

When intended to carry heavy loads, tetrahedral core sandwich plates designed for minimum weight can have a core member yielding as an active failure mode.[4] Consider the lightest yielding core. For simplicity, treat the base material as elastic-perfectly plastic and the core members as pin connected (no moment). These straight members would experience tension or compression only with no bending (irrespective of global loading). Now let failure occur by simultaneous compressive yielding and elastic buckling of any member within the core. The following relation for the lightest (pin-connected) yielding tetrahedral core is found:[7]

$$\left(\frac{\rho_c}{\rho_s}\right)_{\min} = \frac{36\sqrt{2}}{\pi^2}\frac{\sigma_{ys}}{E_s} \qquad [2]$$

DAVID J. SYPECK, Assistant Professor, is with the Aerospace Engineering Department, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114. Contact e-mail: david.sypeck@erau.edu

Manuscript submitted August 27, 2003.

where σ_{ys} and E_s are the yield strength and Young's modulus for the base material, respectively. The ratio σ_{ys}/E_s is the material-dependent yield strain. Observe that the lightest yielding cores are made from low yield strain alloys. Note that for clamped members, the minimum core relative density is divided by four. In practice, the joints normally behave in a fashion intermediate to the pinned (no-moment) and clamped (finite-moment) conditions.

B. *Plain Square Weave Truss Core*

Next, consider a sandwich structure core made up from plain square woven cylindrical filaments of diameter d and opening width w (Figure 5), which are stacked, aligned, and laminated together. The relative density of the core is close to[5]

$$\frac{\rho_c}{\rho_s} = \frac{\pi d}{4(w + d)} \quad [3]$$

For compressed, pin-connected filaments, failure by simultaneous yielding and elastic buckling leads to the following relation for the lightest (pin-connected) yielding plain square weave core:[5]

$$\left(\frac{\rho_c}{\rho_s}\right)_{\min} = \left(\frac{\sigma_{ys}}{E_s}\right)^{1/2} \quad [4]$$

For clamped filaments, the minimum core relative density is divided by two.

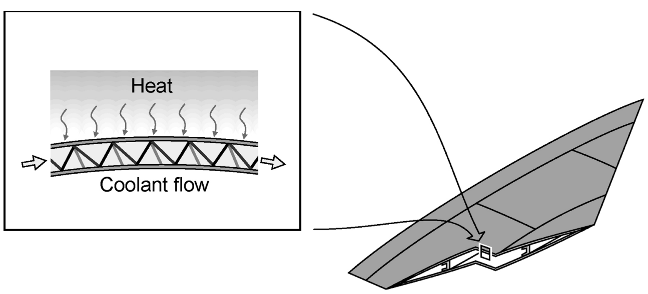


Fig. 1—Multifunctional sandwich panel wingskin. The interconnected porosity within the core provides space for other functionalities such as active cooling.

C. *Weight Comparison*

A weight comparison for both core types is shown in Figure 6 with numerical data for three common engineering alloys[14] presented in Table I. Observe that the tetrahedral architecture produces the lighter yielding core. Furthermore, the minimum relative density range for plain square weaves is well below that of most commercially available meshes. Open cell core structures made from the heavier, woven cores may be better suited for devices such as load supporting heat exchangers, impact energy absorbers, and catalyst scaffolds as opposed to lightweight panels.

D. *Heat Exchange*

Experimental results show that laminated plain square weaves make very efficient (high convection exchange with low pressure drop) convection heat exchanger cores.[15] When made from copper weaves, a thermal performance index (ratio of heat transfer to pressure drop) approximately 3 times higher than that for comparable stochastic copper foam exchangers has been observed.[15] Consider that when plain square woven wire meshes are stacked, aligned, and held together, the situation resembles a bank of aligned cylinders in cross-flow (Figure 7), an efficient, well-proven design. Here, a highly conductive open cell architecture of large accessible surface area is preferred. A turbulent flow of tortuous path also aids convection but requires additional fluid pumping power. For compact applications (*e.g.*, power electronics heat sinks and air conditioners), a small overall size is desired. The surface area density (surface area to volume ratio) is an important parameter for heat exchange systems.[16] For laminated plain square weaves, this is approximately[5]

$$\alpha_A = \frac{\pi}{w + d} \quad [5]$$

suggesting a fine mesh for compact designs (but with a need for additional fluid pumping power). Favorable cell sizes in the millimeter range and relative densities of about 20 pct have been suggested for similar open cell architectures.[8] Materials of choice include aluminum and copper for their

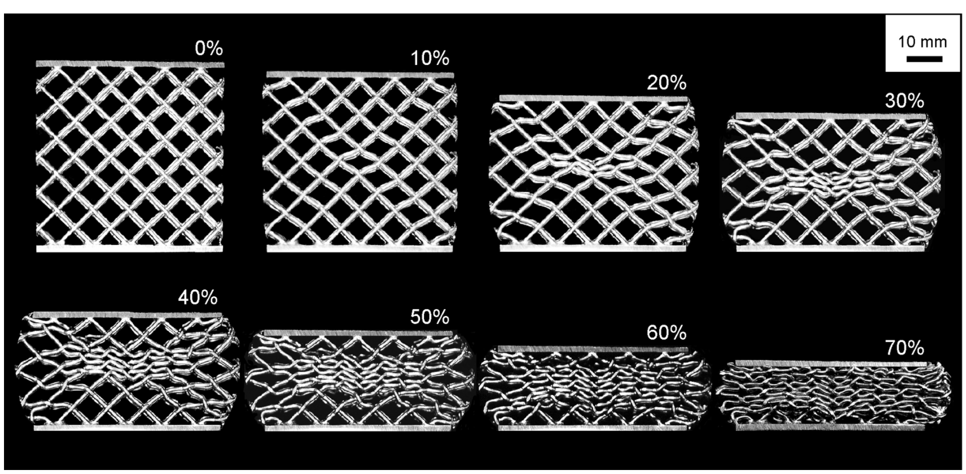


Fig. 2—Quasi-static crushing behavior (percent strains are indicated) for a type 304 stainless steel textile laminate (precrimped diamond weave core with facesheets, 20-ply thick). Comparable details for the fabrication and test method are found in Refs. 5, 7, and 13.

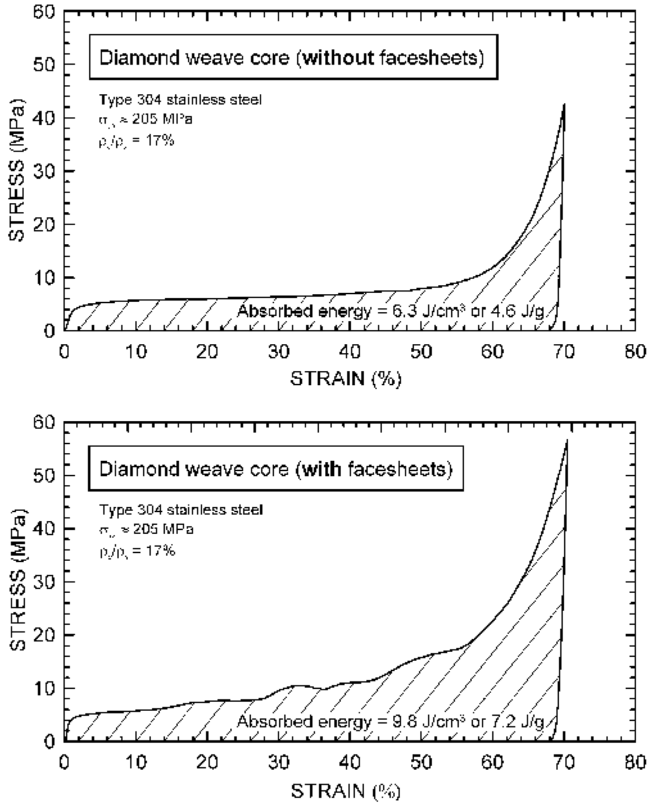


Fig. 3—Stress-strain behavior for the type 304 stainless steel textile laminate. Facesheets restrain the cells from scissoring, leading to a higher energy absorptive capacity (but with a steadily increasing plateau).

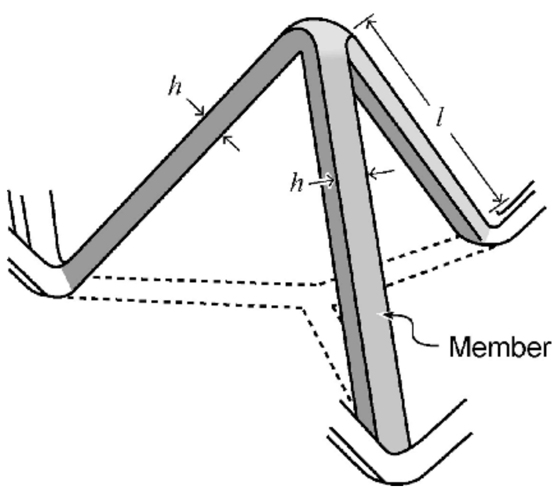


Fig. 4—Tetrahedral unit with square cross-section members. This basic unit repeats itself within the tetrahedral core.

high thermal conductivity. With these thoughts in mind, core fabrication now follows.

III. CORE FABRICATION

A versatile alloy, Al-6061, was chosen primarily for its excellent brazing characteristics, high yield strength-to-weight ratio when precipitation hardened, high thermal conductivity, and long history of successful applications.

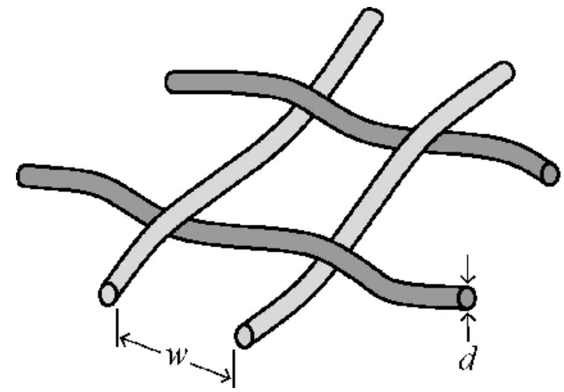


Fig. 5—Plain square weave unit with circular cross-section members. This basic unit repeats itself within the plain square weave core.

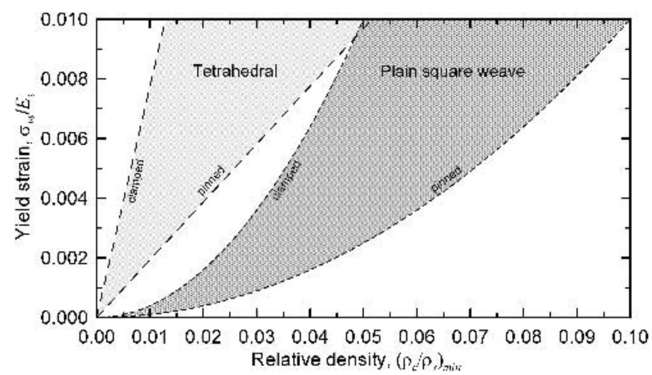


Fig. 6—Weight comparison for tetrahedral and plain square weave cores. The relative density range for the lightest yielding core depends upon core architecture, base material properties, and member connectivity (bounded by the pinned and clamped conditions).

A. *Tetrahedral Truss Core*

In past work, wrought tetrahedral truss cores were made from type 304 stainless steel by ambient temperature (25 °C) stretching of annealed, hexagonally perforated sheets.[7] However, for aluminum alloys, this ambient temperature approach proved difficult owing to cracking (dowel pin punch through at the nodes). With prior difficulties in mind, alternate bending deformation approaches[17,18] were examined.

A standard sheet thickness for Al-6061 and many other alloys is 0.032 in. (0.81 mm). Using Eqs. [1] and [2] with $h = 0.032$ in. (0.81 mm) and representative properties for Al-6061-T6 (Table I), the lightest (pin-connected) yielding tetrahedral core has members of length $l = 11.7$ mm. To fabricate the cores, custom-punched Al-6061 sheets with an elongated hexagonal perforation pattern (Figure 8) were obtained from Woven Metal Products, Inc. (Alvin, TX). The bar widths were 0.81 mm to produce truss members with a square cross section. One set of bars was slightly longer than the others to accommodate a curvature at the nodes induced upon bending. First, the punched sheets were annealed (415 °C for 15 minutes, air cool) to soften the alloy and alleviate cracking upon bending. A slightly modified bending brake with some material removed to accommodate formed truss rows was then used for bending the sheets at the nodes. Within the brake, ≈55 deg angles (the theoretical angle needed for tetrahedrons is 54.7 deg) between adjacent truss

Table I. Properties for Several Common Engineering Alloys[14] along with Relative Density Ranges for the Lightest Yielding Tetrahedral and Plain Square Weave Cores

Wrought Alloy	Density, ρ_s (g/cm^3)	Young's Modulus, E_s (GPa)	Yield Strength, σ_{ys} (MPa)	Yield Strain, σ_{ys}/E_s	Tetrahedral Core $(\rho_c/\rho_s)_{min}$	Plain Square Weave Core $(\rho_c/\rho_s)_{min}$
Type 304 stainless steel (annealed)	8.0	193	205	0.0011	0.0014 to 0.0055	0.016 to 0.033
Al-6061-T6	2.7	69	275	0.0040	0.0051 to 0.021	0.032 to 0.063
Ti-6Al-4V (solution + aging)	4.5	114	1103	0.0097	0.012 to 0.050	0.049 to 0.098

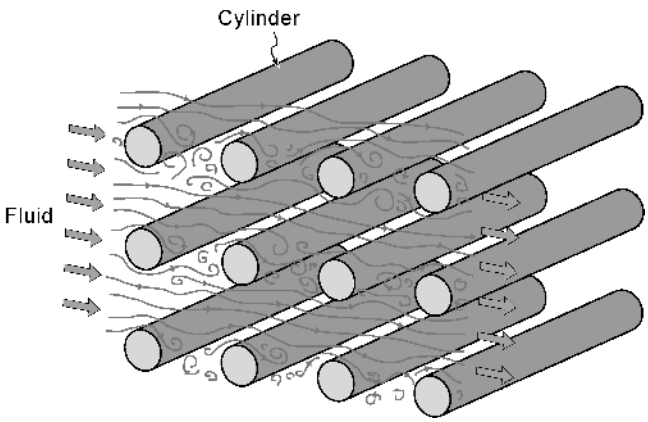


Fig. 7—A bank of aligned cylinders in cross-flow. A similar flow situation arises when plain square weaves are stacked, aligned, and held together.

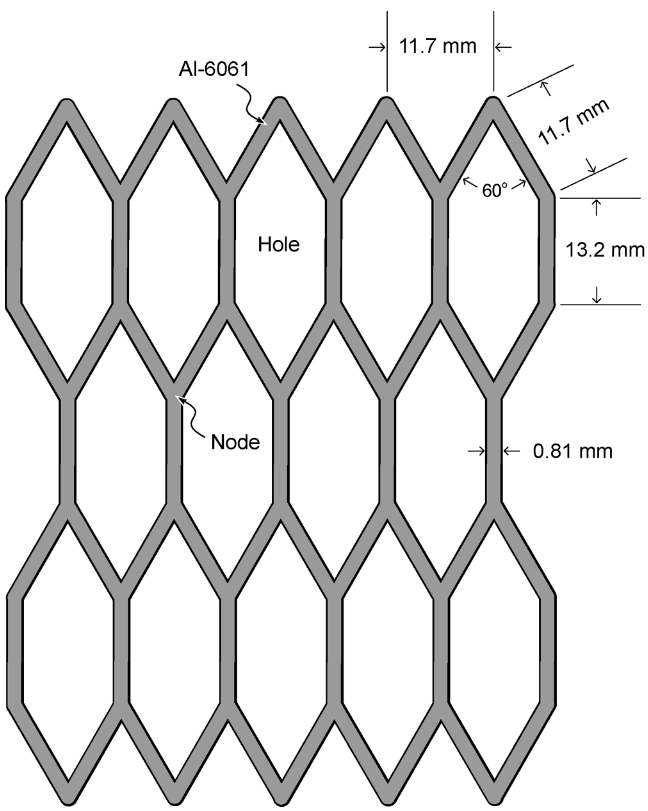


Fig. 8—Perforated sheet design for tetrahedral cores made from Al-6061. The particular dimensions depend upon base material type, sheet thickness, and bending apparatus. This sheet was 0.032-in. (0.81-mm) thick.

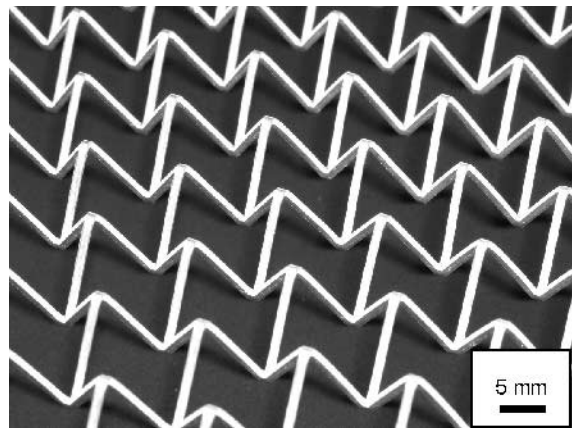


Fig. 9—Al-6061 tetrahedral truss core after bending the perforated sheet. Aligned rows of connected tetrahedral units were obtained in this fashion.

rows were manually introduced. The tetrahedral cores were 10.4 mm high and had relative densities of $\rho_c/\rho_s \approx 0.02$ (before sandwich construction, Figure 9). Owing to the pinned connectivity assumption, core relative densities were at the higher end of the desired range. This conservative approach would tend to promote failure by core yielding as opposed to elastic buckling.

B. *Plain Square Weave Truss Core*

Past experience with fabricating metal textile laminates by stacking, aligning, and joining conventional double crimp weaves has revealed that it can be very challenging to accurately and precisely align the openings. This is particularly true when constructing "large" samples from many individual lamina because alignment errors propagate. The difficulties come about because the weft wire spacing for conventional double crimp weaves is usually somewhat nonuniform. Consider that during weaving, the warp wires are held taught within a reed of prescribed dent such that their final spacing is quite accurate and precise. However, the spacing of the weft wires that pass over and under the warps is often irregular. When attempting to laminate weaves made in this way, it has been repeatedly observed that the weft wires cannot be properly aligned. Moreover, for thin wires spaced far apart, difficulties increase since these lightweight meshes have little rigidity (wires readily shift and move). Issues of this type lead to a poor quality for the final product. Additionally, the warp and weft wires are not always bent by the same amount as they pass over and under one another during weaving. For stacked laminae, incomplete and nonuniform

nodal contacts are seen,[5] which can affect properties (*e.g.*, decreased bond line shear strength). To overcome these practical difficulties, precrimped weaves (spot welding presents another possibility) were selected (Figure 10). The crimps are knuckles in the warp and weft wires that lock the wires into place. They are formed with a crimping machine prior to weaving. Weaves of this type are advantageous because the wire spacing and amount of wire bending are very accurate and precise. Relatively easy pore alignment for these types of meshes leads to high-quality cellular structures with full nodal contact between laminae, albeit at additional cost.

Using the previously cited properties for Al-6061-T6 along with Eq. [3], the lightest pin-connected plain square weave core has $(\rho_c/\rho_s)_{\min} \approx 0.06$. However, this relative density is well below that of most commercially available weaves. Perhaps intermediate crimped weaves (these contain extra crimps between the wire crossovers) would be dimensionally stable at such low relative density because they are firmer than most other types of weaves (the firmness also helps restrict motion of the wires during handling and layup). Their multifunctional performance (*e.g.*, impact energy absorption and flow character) might also be altered by the extra crimping. Resigned to fairly heavy weaves, Al-6061 lock crimp wire cloth was obtained from Cleveland Wire Cloth Co. (Cleveland, OH, Figure 10). The wire diameter was $d = 0.081$ in (2.1 mm), while the opening width was $w = 0.25$ in (6.4 mm). A substantial rigidity as compared to conventional double crimp weaves was apparent with the lock crimp weaves. Using Eqs. [3] and [5], the core relative density should be $\rho_c/\rho_s \approx 0.19$ with the surface area density close to $\alpha_A \approx 370$ m^2/m^3. This anticipated core relative density is close to the range suggested for efficient convection exchange.[8] However, the surface area density is a bit lower than that expected for many compact heat exchange designs (typically having 600 to 6000 m^2/m^3[16]). Thinner wires more closely spaced would increase the surface area density to well within this range.

To construct the cores, ten laminae were stacked, aligned using pins, clamped together, and then machined for facesheet addition. The edges of the cores were oriented to produce a diamond pore configuration for good weight specific stiffness and strength (about twice that of hexagonal honeycomb) when bending the panel in a plane about the pores (apply a point shear load to any node and observe that one-half of the wires are in compression while the other one-half are in tension with no material wasted). Metallurgical bonding of the wires to one another and adjacent laminae was not attempted. The affect on thermal-mechanical performance remains unknown for now, but fabrication appears simpler and less expensive.

IV. SANDWICH CONSTRUCTION

A vacuum brazing approach was used to attach thin facesheets to the tetrahedral and plain square weave cores. The 0.040-in. (1.0 mm) thick facesheets were obtained from Lynch Metals, Inc. (Union, NJ). They were made from precipitation hardenable Al-6951 with a single side Al-4004 braze alloy cladding (~10 pct thickness). This is commonly designated as No. 13 brazing sheet and has a rated optimal brazing range of 582 °C to 599 °C.[19] The AWS classification for the Al-4004 braze alloy is BAlSi-7.[19] Approximate melting ranges for the three involved alloys are shown in Table II. Observe the very small difference (20 °C) between the solidus of the structural alloys (Al-6061 and Al-6951) and liquidus of the brazing alloy (Al-4004). This afforded little opportunity for error upon heating.

The cores were cleaned, placed between the facesheets with the clad sides facing the cores (Figure 11), and a small compressive pressure was applied *via* dead weights. Brazing

Table II. Approximate Melting Range Data for the Involved Alloys[19]

Aluminum Alloy	Solidus (°C)	Liquidus (°C)
Al-6061	616	652
Al-6951	616	654
Al-4004	554	596

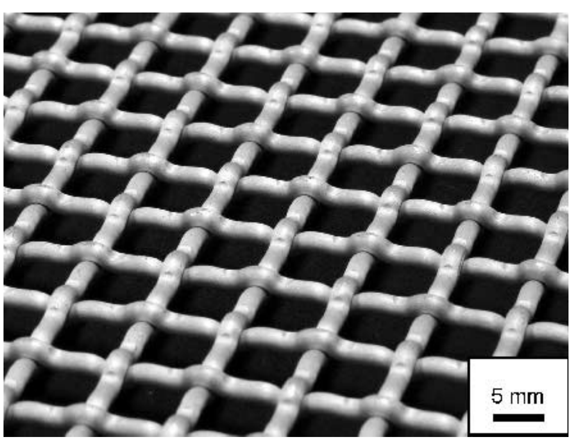


Fig. 10—Al-6061 lock crimp weave (as received). The crimps are knuckles in the warp and weft wires that lock the wires into place for accurate alignment upon laminating.

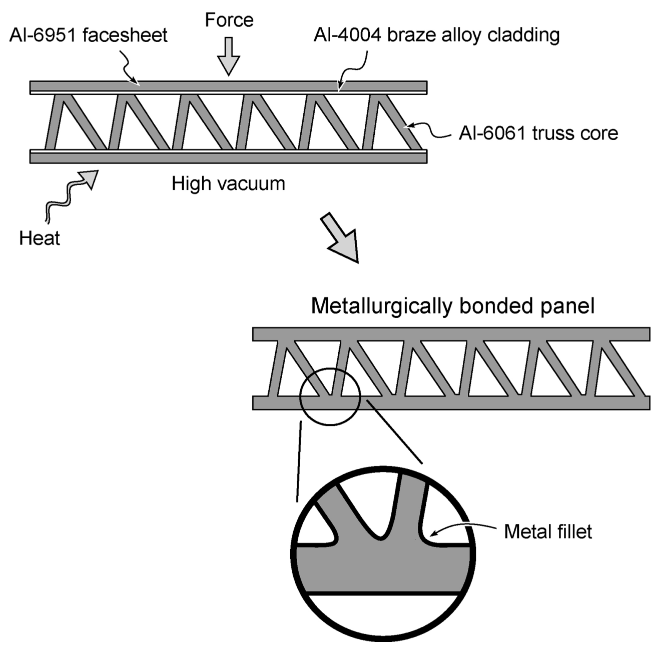
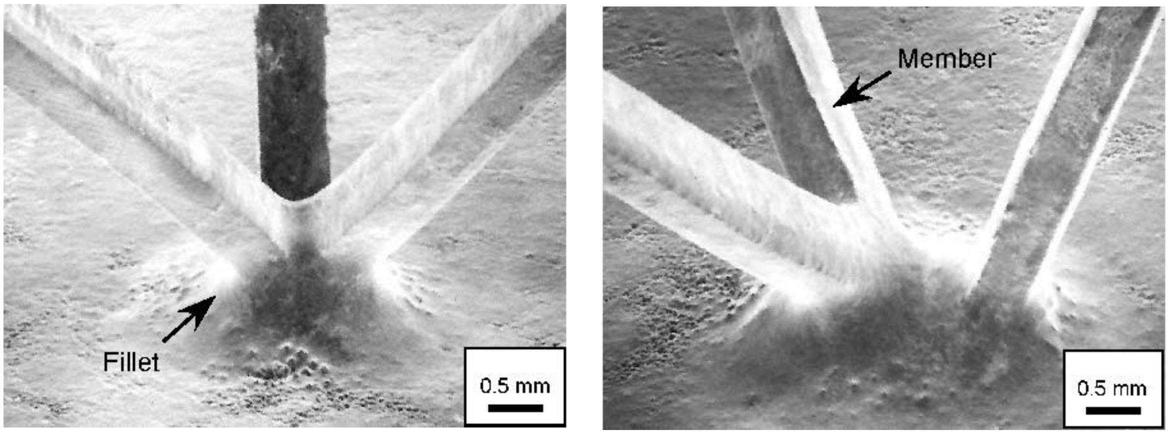
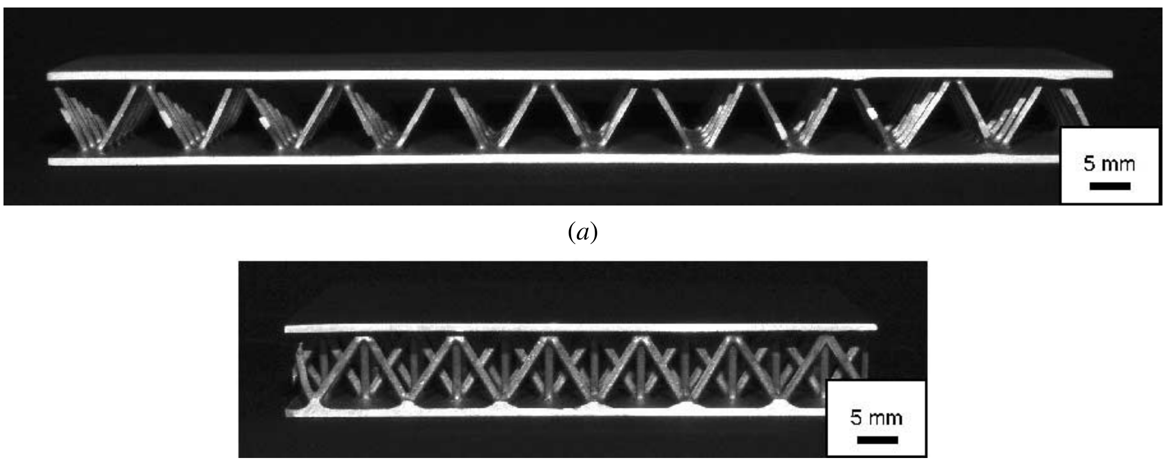


Fig. 11—Sandwich construction technique. The aluminum alloy cores were placed between braze clad aluminum alloy facesheets and heated under argon and then high vacuum.



(*a*) (*b*)

Fig. 12—Typical core-facesheet bond for an aluminum alloy sandwich structure with a tetrahedral core. Capillary forces drew the melt to the joints producing large curvature radius fillets (to resist cracking): (*a*) end view and (*b*) side/angle view.

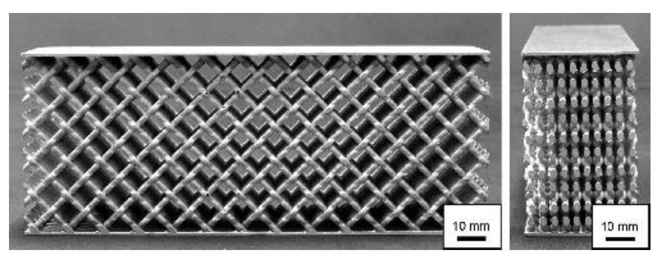


(*a*)

(*b*)

Fig. 13—Aluminum alloy sandwich structure with a tetrahedral core: (*a*) side view and (*b*) end view.

occurred within a metallurgical vacuum furnace (molybdenum hot zone). Initially, samples were heated under periodic argon purging at a rate of 20 °C/min to 150 °C to flush away impurities and H_2O vapor. Then, heating occurred at a rate of 20 °C/min to 350 °C under partial Ar pressure in the range of 2.0 to 2.5×10^{-2} torr for additional cleaning. Samples were then heated at a rate of 20 °C/min to 450 °C under high vacuum and held there until a vacuum level in the range of 10^{-5} torr had been achieved. Final heating occurred under high vacuum at 10 °C/min until melting of the clad braze alloy at approximately 600 °C. Heating was then ceased and the samples were allowed to cool within the furnace under high vacuum. At the brazing temperature, the melt coated the interior surfaces of the facesheets and capillary forces preferentially drew it to points of core/facesheet contact. Filleted joints of large curvature radius (to resist cracking) were made (Figure 12). The fabricated sandwich panels are shown in Figures 13 and 14. The heights of the tetrahedral cores were slightly decreased (with a slight increase in core density) to about 9.7 mm owing to the triads flattening at their peaks and embedding themselves into the melt. Virtually



(*a*) (*b*)

Fig. 14—Aluminum alloy sandwich structure with a plain square weave core (diamond configuration): (*a*) front view and (*b*) side view.

no difference in core height was observed for the plain square weave cores after construction.

V. SUMMARY

Metal deformation, assembly, and joining processes have been used to fabricate truss core sandwich structures from

wrought, heat-treatable aluminum alloys. Tetrahedral cores were made by bending perforated aluminum alloy sheets. Plain square weave cores were made by stacking and aligning precrimped aluminum alloy weaves. Both core types were metallurgically bonded between braze clad aluminum alloy facesheets using a vacuum brazing approach. This fabrication method produced filleted joints of large curvature radius to resist cracking at points of core/facesheet attachment. The tetrahedral core architecture appears flexible enough for making complex curved sandwich structures. The heavier, plain square weave architecture, may be better suited for multifunctional applications such as load supporting heat exchangers. A significant advantage with ease of alignment and final sample quality was obtained using precrimped weaves. By using wrought metals and proven joining methods, performance advantages over cast metal counterparts are anticipated and at reduced cost.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of this work through DARPA/ONR Research Grant No. N00014-01-1-0517 and the ERAU Internal Research Fund.

REFERENCES

1. A.G. Evans: *MRS Bull*., 2001, Oct., pp. 790-97.
2. J.C. Wallach and L.J. Gibson: *Int. J. Solids Structures*, 2001, vol. 38, pp. 7181-96.
3. V.S. Deshpande and N.A. Fleck: *Int. J. Solids Structures*, 2001, vol. 38, pp. 6275-6305.
4. N. Wicks and J.W. Hutchinson: *Int. J. Solids Structures*, 2001, vol. 38, pp. 5165-83.
5. D.J. Sypeck and H.N.G. Wadley: *J. Mater. Res*., 2001, vol. 16 (3), pp. 890-97.
6. S. Chiras, D.R. Mumm, A.G. Evans, N. Wicks, J.W. Hutchinson, K. Dharmasena, H.N.G. Wadley, and S. Fichter: *Int. J. Solids Structures*, 2002, vol. 39, pp. 4093-4115.
7. D.J. Sypeck and H.N.G. Wadley: *Adv. Eng. Mater*., 2002, vol. 4 (10), pp. 759-64.
8. A.G. Evans, J.W. Hutchinson, N.A. Fleck, M.F. Ashby, and H.N.G. Wadley: *Progr. Mater. Sci*., 2001, vol. 46, pp. 309-27.
9. M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, and H.N.G. Wadley: *Metal Foams: A Design Guide*, Butterworth-Heinemann, Boston, MA, 2000.
10. L. Christodoulou and J.D. Venables: *JOM*, 2003, Dec., pp. 39-45.
11. *HexWeb™ Honeycomb Attributes and Properties*, Publication No. TSB 120, Hexcel Composites, Pleasanton, CA, 1999.
12. M.L. Renauld, A.F. Giamei, M.S. Thompson, and J. Priluck: *Porous and Cellular Materials for Structural Applications*, Materials Research Society Symposia Proceedings 521, D.S. Schwartz, D.S. Shih, A.G. Evans, and H.N.G. Wadley, eds., Materials Research Society, Warrendale, PA, 1998, pp. 109-17.
13. D.J. Sypeck: in *Processing and Properties of Lightweight Cellular Metals and Structures*, A. Ghosh, T. Sanders, and D. Claar, eds., TMS, Warrendale, PA, 2002, pp. 35-45.
14. *Adv. Mater. Processes*, 2000, vol. 158 (6).
15. J. Tian, T. Kim, T.J. Lu, H.P. Hodson, D.T. Queheillalt, D.J. Sypeck, and H.N.G. Wadley: *Int. J. Heat Mass Transfer*, 2004, vol. 47, pp. 3171-86.
16. T.J. Lu, H.A. Stone, and M.F. Ashby: *Acta Mater*., 1998, vol. 46 (10), pp. 3619-35.
17. K, Tashiro: U.S. Patent No. 6,207,256 B1, Mar. 27, 2001.
18. S.T. Brittain, Y. Sugimura, O.J.A. Schueller, A.G. Evans, and G.M. Whitesides: *J. Microelectromech. Systems*, 2001, vol. 10 (1), pp. 113-20.
19. *Aluminum Brazing Handbook*, 4th ed., The Aluminum Association, Washington DC, 1990.