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Mechanical behaviour of tube-woven Kagome truss cores under compression

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ABSTRACT

Wire-woven bulk Kagome (WBK) has recently been used to fabricate multi-layered truss-type cellular metals. A tube WBK structure is fabricated of tubes instead of solid wires. In this work, tube WBK specimens with various combinations of slenderness ratio and inner-to-outer diameter ratio of the tubular struts were tested under compression to investigate the effects of geometric factors on peak strength, equivalent Young's modulus and energy absorption capability. To aid in the physical interpretation of the results and the development of a design methodology, numerical simulations of single tubular struts were performed with a wide range of slenderness ratio and inner-to-outer diameter ratio. The tube WBKs outperformed most cellular metals, but they were inferior to hollow trusses, especially those with a diamond configuration. However, energy absorption of the tube WBKs was comparable to that of hollow trusses because of stable deformation of the tube WBKs after initial yielding or maximum strength.

1. Introduction

Periodic cellular metals (PCM) are useful sandwich core materials in terms of strength and lightness. PCMs are classified as prismatic or truss-based [1]. The open cell structure of the latter is an advantage because the interior space is accessible for additional functions such as heat transfer media [2,3] or catalyst supports [4]. To enhance resistance against strut buckling (a main failure mechanism of truss PCMs), tubes can be used as raw material because they increase the second moment of inertia of the cross-sectional area for a given weight. The "hollow truss core" developed by Queheillalt et al. [5–7], is a good example. Using tubes has additional benefits. Tubes give the flexibility of changing density without changing unit cell size and enhance the bonding strength between the cores and face sheets through large surface interfacial area nodes. A multi-layered hollow truss core can be simply fabricated by aligning tubes in collinear layers with an alternating orientation of successive layers to create a lattice truss architecture [6]. Despite excellent performance in terms of specific strength and energy absorption capability, hollow truss cores have high anisotropy; that is, the material properties are quite sensitive to orientation.

Wire-woven bulk Kagome (WBK) is a multi-layered truss PCM fabricated by a three-dimensional (3-D) assembly of wires rather than by stacking multiple single-layered truss structures [8]. Helically-formed wires are screw-inserted in six evenly distributed directions in space to fabricate a Kagome truss-like structure in which the wires cross one another with minimum deflection. Consequently, the strength is only slightly degraded compared to an equivalent ideal configuration composed of straight struts and the material anisotropy is minimized. Moreover, WBK has good potential for mass-production. The effects of geometric factors such as wire diameter and pitch on the compressive strength of WBK has been investigated [9]. WBK composed of high strength steel and filled with brass has been developed to attain ultra-high specific strength [10]. Heat transfer characteristics under forced convection [11] and the methodology for optimal design [12,13] for sandwich panel cores were reported. In addition, it was recently shown that WBK could be fabricated using tubular wires and the strength was as good as that estimated using an analytic solution derived for equivalent Kagome truss PCMs with an ideal configuration composed of straight tubular struts [14].

In this work, tube WBK specimens with nine different combinations of slenderness ratio and inner-to-outer diameter ratio of tubular struts were tested under compression to investigate the effects of geometric factors on peak strength, equivalent Young's modulus and energy absorption capability. To aid in the physical interpretation of the results and the development of a design methodology, numerical simulations for single tubular struts were performed using a wide range of slenderness ratio and inner-to-outer diameter ratio. A map was created showing contours of the relative densities and the normalized peak strengths of tube WBKs and the domains of their failure modes plotted as functions of d_o/c and d_i/d_o. Another map was constructed showing relative densities and equivalent Young's moduli of tube WBKs. The measured results of the tube WBKs were compared to other cellular metals with respect to strength and energy absorption capability.

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2. Experimental procedures

2.1. Specimen preparation

WBK specimens were fabricated from medical grade 304 stainless steel tubes. In the first step, continuous helical tubes were formed. Three identical tubes were twisted together until plastic deformation occurred in the tubes, and then were separated from one another. Residual plastic deformation after twisting made the helical shape. Next, the helical tubes were assembled. The tubes were assembled in three directions into a two-dimensional (2-D) Kagome truss layer in a plane. The multiple layers were stacked one-over-one with an interval, and additional tubes were inserted in three out-of-plane directions to create a 3-D Kagome-like structure. At each cross point three tubes pass each other with minimum deflection. Fig. 1 shows typical examples of tube WBK specimens. The detailed fabrication procedure is described in the authors' previous works [8]. Finally, the tube assemblies were metallurgically bonded using a brazing technique. An aqueous mixture of Nicrobraz® 51 (BNI-12) filler metal powder and cement (Wall Colmonoy Corp.) was sprayed over the tube assemblies and dried in an oven at 110 °C. Vacuum brazing was carried out for 225 min in a furnace at 10^{-4}–10^{-5} Torr. During first 90 min, the furnace was heated from room temperature to 930 °C and maintained at this temperature for 15 min. The temperature was then increased to 1040 °C for 15 min and maintained for 15 min. Finally, the furnace was slowly cooled down to room temperature for 90 min.

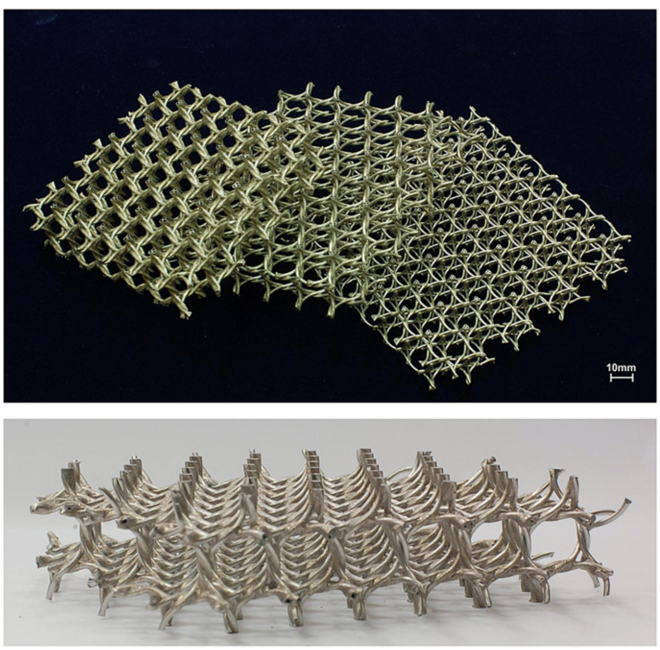

Fig. 1. Tube WBK specimens composed of three different tubes (top) and a side view of the middle one (bottom).

Three kinds of tubes with outer/inner diameters of $d_o/d_i = 0.82/0.56$, 1.0/0.7 and 1.27 mm/0.99 mm were used to fabricate the WBK specimens. The pitches, which were twice the strut lengths, c, ranged from $2c = 9.9$ to 25.6 mm. Nine different types of the specimens were prepared. Two or three experiments per specimen type were performed. All the helically-formed wires used to fabricate a given specimen have an identical pitch, inner diameter and outer diameter. Therefore, the angles among struts in all the specimens are constant regardless of the pitch. All the specimens had two layers (i.e., two half-layers on the top and bottom and one layer in the middle). Table 1 lists the geometric parameters of the tested specimens. Fig. 2 shows photos of the specimens and their cross sections at the cross points among tubes. The numbers labeled on the photos correspond to those in the leftmost column of Table 1. The three photos in a row (numbered as 1–9) show specimens fabricated with identical tubes of a given inner/outer diameter. The strut lengths, c, were intentionally designed to give three relative densities, $\rho_{rel} \sim 0.64\%$, 1.55% and 2.44%, theoretically calculated for the specimens composed of tubes of a given inner/outer diameter ratio. In the final specimens, the densities were increased by the filler metal supplied at the cross points among tubes to $\rho_{rel} \sim 0.7\%$, 1.8% and 2.9% in the fabricated specimens. Two face sheets were attached to the top and bottom surfaces of a WBK specimen in preparation for a uniaxial compression test. For the face sheets, SUS 304 plate of 3 mm thickness, which is a material similar to the helical tubes, was selected. Epoxy, AXIA EP-04 (Magnolia Plastic Inc.), was used as an adhesive to attach the sheets.

2.2. Uniaxial compression tests

All compression tests were performed on an Instron 880 electric–hydraulic material test system. The load and displacement were recorded by a data acquisition board embedded in a personal computer. The measurement and control software was coded in the HP VEE language (Agilent Technologies®). A 250 kN load cell was used for the test, and all of the specimens were compressed between two steel circular compression platens. The diameter of each platen, $D = 200$ mm, was sufficiently larger than the specimen sizes. A displacement rate of 0.005 mm/s was applied on the bottom surface of each specimen as an external loading. All specimens were loaded up to 60% of the strain to obtain their

Table 1
Geometric parameters of the tube WBK and solid WBK specimens tested under compression.

Specimen no.	d_o (mm)	d_i (mm)	c (mm)	Relative density (%)		d_i/d_o	d_o/c	Cross section area (mm^2)
				Calculated	Measured			
1	0.82	0.56	9.66	0.64	0.73	0.68	0.085	0.282
2	0.82	0.56	6.24	1.55	1.83	0.68	0.131	0.282
3	0.82	0.56	4.95	2.44	2.84	0.68	0.166	0.282
4	1	0.7	12.1	0.64	0.70	0.7	0.082	0.401
5	1	0.7	7.81	1.55	1.77	0.7	0.128	0.401
6	1	0.7	5.9	2.44	2.86	0.7	0.169	0.401
7	1.27	0.99	12.8	0.64	0.73	0.78	0.099	0.497
8	1.27	0.99	8.29	1.55	1.86	0.78	0.153	0.497
9	1.27	0.99	6.57	2.44	2.89	0.78	0.193	0.497
S1	0.78	0	12.6	0.64	0.72	0	0.062	0.478
S2	0.78	0	8.1	1.55	1.80	0	0.096	0.478
S3	0.78	0	6.45	2.44	2.84	0	0.121	0.478