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Structural nanocrystalline Ni coatings on periodic cellular steel

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ABSTRACT

This study develops a new type of hybrid material that is a composite of a plain carbon steel micro-truss and a structural nanocrystalline Ni coating. The plain carbon steel micro-truss was made by a simple stretch–bend sheet forming method. It created a low density cellular material (~5% relative density), combining the low embodied energy and cost of the starting precursor material with the structural efficiency of pyramidal micro-truss architecture. The nanocrystalline Ni structural coating was designed to provide both corrosion protection and inelastic buckling resistance. Because the ultra-high strength material was optimally located at the furthest distance from the neutral bending axis, only a thin coating of nanocrystalline Ni (~50 μm) is needed to double the inelastic buckling resistance of the 1.13 mm × 0.63 mm plain carbon steel struts.

1. Introduction

The growing demand for limited resources and energy will increasingly become the drivers for the development of new types of hybrid materials. Energy in particular is a critical driver since it is required at every stage from material production through product manufacture, use and disposal, e.g. Ashby [1,2]. Plain carbon steels are a good place to start in the development of new hybrid materials; primary production is conducted on a massive scale and their embodied energy is amongst the lowest of any structural metal (significantly below lightweight alloys of Mg, Al, and Ti, e.g. [2,3]). On the other hand, the structural efficiency of cellular metals can be used to reduce energy consumption in areas such as transportation applications (e.g. [4,5]). A hybrid of open-space and steel would create a lightweight cellular material that combines the low embodied energy of the material production stage with the potential to reduce energy consumption at the product use stage.

Several different routes have been attempted to produce cellular steel (e.g. [6–10]). For example, gas pockets in plain carbon steel have been inserted through the thermal decomposition of high temperature foaming agents such as $MgCO_3$ and $SrCO_3$ [6] and by the production of CO and CO_2 within sintered powder compacts of iron, graphite, and hematite [7]. These methods have produced closed-cell architectures having relative densities from 38% to 64% [6] and down to 45% [7]. Alternatively, pre-fabricated hollow steel spheres have been sintered together, forming 32–39% [8] and ~5% [9] relative density compacts. In addition, 25% relative density open-cell architectures have been fabricated by sintering chopped steel fibres [10].

The present study uses a simple approach to produce low density and open-cellular plain carbon steel. Perforated sheet precursors are plastically deformed into a three-dimensional micro-truss using a modified stretch–bending method that was initially developed by Sypeck and Wadley [11]. This approach has the advantages that a wide range of cellular architectures can be fabricated from a single mechanical press and that the cold work imparted to the struts during fabrication can be used as an in situ microstructural strengthening mechanism [12]. More significant, however, is that the cellular architecture of micro-truss materials are specifically designed such that the internal struts are primarily loaded in compression or tension; the stretch-dominated loading characteristics of micro-trusses can be an order of magnitude more efficient than the bending-dominated behaviour of conventional metal foams [13].

However, periodic cellular plain carbon steel would be expected to exhibit the same poor corrosion resistance as the starting precursor material. Electroplated coatings such as nickel, chromium, zinc, and tin are widely used to improve the corrosion resistance of steels [14]; while these metals can not match the embodied energy of the substrate, they represent a comparatively small energy trade-off in order to greatly modify the chemical properties of the surface. In particular, an electrodeposited nanocrystalline Ni coating may be able to provide more than just corrosion protection; it may also provide enhanced mechanical stability because of the nearly order of magnitude strength increase that can be obtained in Ni by grain size reduction to the nm-scale [15]. In this scenario, the coating would act as an ultra-high strength skin encapsulating

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the periodic cellular steel micro-truss, effectively creating a composite micro-truss. This approach may be most effective in cases where failure occurs by inelastic buckling, since the nanocrystalline Ni would be optimally located away from the neutral bending axis of the strut. The present study is a first examination of the potential of multifunctional structural coatings on plain carbon periodic cellular steel.

2. Experimental

Perforated AISI-SAE 1006 low carbon steel (sheet thickness $t_o = 0.66 \pm 0.01$ mm) was purchased from McNichols Perforated Products (Atlanta, GA). The 25.81 mm^2 square perforations were punched on a two-dimensional square lattice of unit cell size 6.35 mm × 6.35 mm, creating an open area fraction of $\phi = 0.64$. The pyramidal cores (strut geometry shown in Fig. 1) were fabricated by deforming alternating nodes above and below the starting plane using a modified stretch–bending process, details in [16]. Miniature test coupons were also cut from the as-received sheet and measured in tension, after [16].

Nanocrystalline Ni was pulse current electrodeposited around the struts and nodes of the steel micro-trusses, after [17,18]. Reference coupons (electroplated using the same deposition conditions as the steel micro-truss) were characterized by X-ray diffraction (XRD) using cobalt K_α X-rays ($\lambda = 0.179$ nm) and by transmission electron microscopy (TEM) at an accelerating voltage of 200 kV. TEM foils were prepared by jet polishing with a 10% perchloric acid, 15% acetic acid, and 75% methanol electrolyte at 253 K and an applied voltage of 20 V. A nominal thickness for the electrodeposited nickel was calculated based on the increase in mass during the plating process by assuming a uniform thickness of nickel over the entire surface area of the micro-truss, i.e., $t_{Ni} = m/S_A\rho_{Ni}$, where m is the electrodeposited mass, S_A is the electroplated surface area, and ρ_{Ni} is the density of nickel. A range of nominal coating thicknesses, from 19.5 ± 0.3 μm to 60.1 ± 0.2 μm, was obtained by adjusting the deposition time.

Microhardness measurements were made on strut cross-sections that had been mounted in epoxy and prepared using standard metallographic methods. Measurements were taken using an MHV 2000 microhardness tester with a 0.49 N applied load and 10 s dwell time. Uniaxial compression testing was performed at a cross-head displacement rate of 1 mm/min. Stand alone PCM cores were tested using confinement plates (i.e., recessed channels in steel compression plates that rigidly lock the truss-core nodes in place – details in Refs. [19,20]). This test method can be used to simulate the mechanical performance that stand-alone truss-cores would exhibit in a sandwich structure [19,20]. A subset of samples were loaded to strains of up to $\varepsilon \approx 0.7$ and characterized by scanning electron microscopy (SEM).

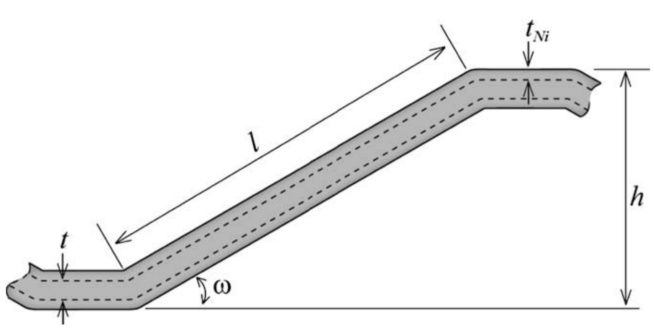

Fig. 1. Schematic diagram of a micro-truss strut, showing truss height (h), strut length (l), strut thickness (t), truss angle (ω), and deposited nickel coating thickness (t_{Ni}).

3. Results and discussion

The range of micro-truss architectures that can be fabricated by stretch–bending from a given starting sheet is limited by the useful plastic deformation that can be input to the struts [16]. This is illustrated in Fig. 2 which presents a stretch–bend forming curve showing the fabrication force as a function of press displacement. After an initial stage of elastic bending, the perforated sheet begins to plastically deform around the press pins. This first stage of plastic deformation is bending-dominated and its onset can be modeled after the force required to initiate a plastic hinge in a simple cantilever beam [16]. Beyond this point there is a gradual transition to stretch-dominated deformation and the forming force continues to increase until one or more struts have failed by tensile instability [16]. The end of useful plastic deformation (and the limit of formability) can be defined by the maximum force and the corresponding maximum displacement, d_M. For the as-received perforated steel sheet, strut failure occurred adjacent to the forming pin at a maximum displacement of $d_M = 3.86 \pm 0.03$ mm, which corresponded to a relative density of 5.3%.

An even broader range of plain carbon steel micro-truss architectures would be attainable through intermediate annealing treatments and optimal pin design. For example, in conventional stretch–bending, the formability improves significantly with increasing punch radius of curvature R for a constant sheet thickness [21,22]. This is due to the increased uniformity of the strain distribution around the punch shoulder, which increases the limit strains by modifying the instability criterion and delaying the formation of a local neck. Decreasing the stretch–bend ratio t_o/R has been shown to shift the site of fracture from near the punch contact, i.e., where combined bending and stretching strains occur, to the side-wall region undergoing pure stretching. This failure mode may permit the greatest range of stretch–bend formed micro-truss architectures [16]. Finally, developing stretch–bending methods to accommodate expanded rather than perforated metal would represent a more effective use of the starting material.

A conservative upper forming limit of $0.95d_M$ ($d = 3.66$ mm) was selected for making all the micro-trusses in the present study. This corresponded to an as-fabricated relative density of 5.9% and a

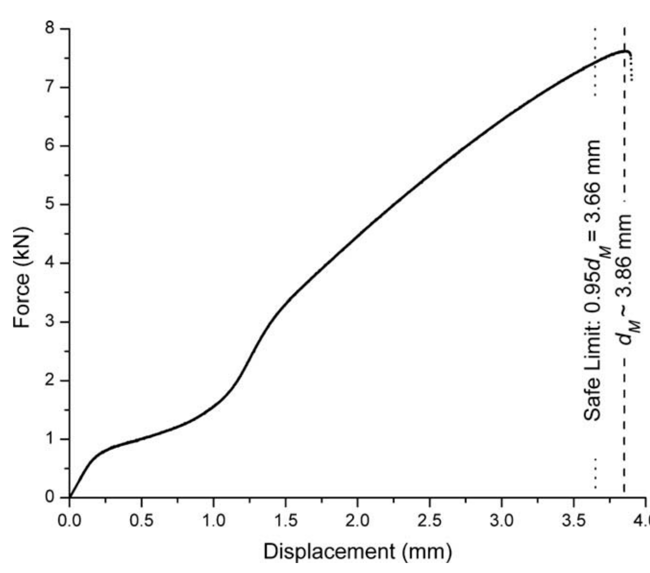

Fig. 2. Typical force–displacement stretch–bend forming curve of the plain carbon steel micro-trusses. Strut fracture near the press pin occurred at the maximum forming displacement d_M. A conservative upper forming limit of $0.95d_M$ was selected for the micro-trusses of the present study, which corresponded to a relative density of $\rho_R = 5.9\%$ and truss angle of $\omega = 35°$.