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Viewpoint Paper

Reinforcement of microtruss cellular materials by nanocrystalline electrodeposition

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Abstract—Compositionally graded microtruss cellular materials can be created by electrodepositing ultrahigh-strength sleeves of nanocrystalline material over precursor microtruss cores. Due to their position relative to the neutral axis of the struts, even relatively thin coatings can provide significant strength and weight benefits to the precursor assembly. Using nanocrystalline nickel as an example, the questions of strength prediction, performance increase, sleeve/core delamination and sleeve fracture are discussed.

Keywords: Buckling; Cellular materials; Modelling; Nanocrystalline metal; Finite element analysis

1. Introduction

Electrodeposition is becoming established as a mature technology for the production of ultrahigh-strength nanocrystalline materials [1]. Grain size reduction to the nanometer scale can result in large yield strengths (up to 1200 MPa for Ni-based alloys [1]), while retaining reasonable ductility (uniform plastic strains on the order of 5% are typical [1]). Moreover, electrodeposition is a non-line-of-sight technique; an encapsulating high-strength sleeve of nanocrystalline material can be deposited on nearly any preform geometry. This means that nanocrystalline electrodeposition is well suited to the reinforcement of microtruss architectures. Because the high-strength electrodeposited sleeve is optimally positioned away from the neutral bending axis of the microtruss struts, significant weight specific strength increases can be obtained, despite the comparatively high density of the reinforcement [2]. An important issue in the development of these composite microtrusses is to determine which core materials can be reinforced most effectively by nanocrystalline electrodeposition. This analysis is made more difficult by the interaction of competing failure mechanisms. The present article provides an overview of these issues by examining the specific strength increases that are possible when steel and aluminum microtrusses are reinforced with electrodeposited nanocrystalline Ni.

Microtruss unit cells are designed in such a way that external loads are resolved axially along the strut members, allowing these materials to possess enhanced weight-specific properties compared to conventional metal foams [3]. Microtruss assemblies are typically used as cores in sandwich panels. The latter can fail in one of three modes: facesheet wrinkling and yielding, core failure and core–facesheet shear [4]. Since this study is focused on material selection for microtruss cores, the failure of truss core members is the most relevant type of failure mechanism. The struts of microtruss cores generally fail by tensile or compressive yielding and by buckling [5]. Since the buckling strength of a slender column in compression will typically be substantially lower than the yield strength of the material, it is the critical buckling stress of the composite strut that will largely determine the overall mechanical properties.

2. Buckling strength and density of composite columns

The simplest failure mechanism of an electrodeposited composite column is elastic buckling. Assuming that the starting core has a square cross-section and that the coating has uniform thickness, the critical elastic buckling strength of the hybrid column (σ_{CR}^{H}) can be given by [2,6]:

$$\sigma_{CR}^{H} = \frac{k^2\pi^2\left(E_S\left(\frac{1}{1-f_S} - 1 + f_S\right) + E_C(1-f_S)\right)}{(L/r_C)^2} \quad (1)$$

where k is a constant which describes the rotational stiffness of the ends of the column (e.g. $k = 1$ for pin-jointed conditions and $k = 2$ for rigid ends), E_S and E_C are the

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elastic moduli of the sleeve and core respectively, f_S is the area fraction of the sleeve, and L/r_C is the slenderness ratio of the starting core. The radius of gyration r_C is a function of the second moment of area and cross-sectional area of the core (I_C and A_C respectively), and is given by $r_C = \sqrt{I_C/A_C}$. The density of the hybrid (ρ^H) is related to the density of the sleeve and core (ρ_S and ρ_C respectively) by:

$$\rho^H = \rho_S f_S + \rho_C(1 - f_S) \quad (2)$$

The material performance parameters mentioned above can then be represented as analytical functions of geometric properties, material properties and the end constraint constant.

However, microtruss struts typically have intermediate slenderness ratios (on the order of 15–55 [2,4,5,7–17]), and failure often occurs by inelastic buckling [2,4,8–13]. In this case, the Young's moduli of the sleeve (E_S) and core (E_C) in Eq. (1) are replaced by the respective tangent moduli, $E_{T,S}$ and $E_{T,C}$, so material properties are no longer constant parameters. The values of the tangent moduli (and corresponding critical buckling stresses and strains) are dependent on the geometry of the composite column and the particular value of the end constraint; it is thus not possible to fully separate material and geometric parameters, increasing the complexity of sleeve/core material selection.

The effects of material non-linearity, strut geometry and end constraint are illustrated in Figure 1 for the case of a low-carbon steel strut reinforced with 20 nm grain size nanocrystalline Ni (material properties given in Ref. [2]). The critical buckling stress is found at the intersection of Eq. (1) (where the tangent moduli of both materials are a function of strain) and the normal stress in the composite column (given by the isostrain assumption $\sigma(\varepsilon) = \sigma_S(\varepsilon)f_S + \sigma_C(\varepsilon)(1 - f_S)$, where σ_S and σ_C are the sleeve and core stresses respectively). The elastic–plastic properties of the sleeve and core materials define three buckling regimes in Figure 1: elastic sleeve/elastic core ($\varepsilon_{CR} \leqslant 0.0008$, Zone 1), elastic sleeve/inelastic core ($0.0008 < \varepsilon_{CR} \leqslant 0.003$, Zone 2) and inelastic sleeve/inelastic core ($\varepsilon_{CR} > 0.003$, Zone 3). For the uncoated $L/r_C = 55$ column in Figure 1, the critical buckling strains (defined by the $k = 1$ ($\varepsilon_{CR} = 0.0013$) and $k = 2$ ($\varepsilon_{CR} = 0.0022$) limits) fall within a Zone 2 band. Note that the actual end condition of struts in microtruss materials will have a value that is intermediate to these two limits (e.g. [3]), and will depend on factors such as hinge curvature, strut cross-section and strut angle. The nanocrystalline sleeve increases the critical buckling strains by an amount that depends on the material properties of the core and sleeve, the strut geometry and the end constraint. For instance, at $f_S = 0.1$, a pin-jointed ($k = 1$) column fails by elastic sleeve/inelastic core buckling (Zone 2). Shifting to either a rigid-jointed boundary condition ($k = 2$) or a thicker nanocrystalline sleeve changes the failure mechanism into inelastic sleeve/inelastic core buckling (Zone 3).

An envelope of achievable material performance can therefore be defined by the $k = 1$ and $k = 2$ boundary conditions for hybrid struts. The width of this envelope is a complex function of the strain dependence of tangent modulus in both materials and the sleeve/core geometry. Figure 2 illustrates these strengthening envelopes for low-carbon steel and 3003 aluminum alloy cores ($L/r_C = 15$ and 55) reinforced with nanocrystalline Ni sleeves of $0 \leqslant f_S \leqslant 0.9$ (material properties described in Ref. [2]). One metric that can be used to evaluate the efficiency of the reinforcement material is the strength increase per unit density ($\Delta\sigma/\Delta\rho$), which is equal to the initial slope of the envelopes shown in Figure 2. The strength increase per unit density is higher when the sleeve is deposited on steel precursors, because the additional strength is associated with a relatively small increase in density. The relative change in weight-specific strength (i.e. the ratio of the strength/density of the hybrid relative to the core $((\sigma/\rho)^H/(\sigma/\rho)^C)$ is a second metric that can evaluate the reinforcement efficiency. Note that, for a given slenderness ratio, the sleeve is more efficient at increasing the specific strength of the aluminum alloy core, because the same amount of strength increase per unit density is more effective in increasing the strength to density ratio of the material with lowest density. Finally, if symmetric tensile–compressive loading is considered among the struts of the microtruss, inelastic buckling will be the dominant failure mechanism when the stress in the sleeve is lower than the tensile strength of the material (occurring at a strain of $\varepsilon = 0.006$); buckling stresses that satisfy this condition are shown as solid lines in the envelopes of Figure 2.

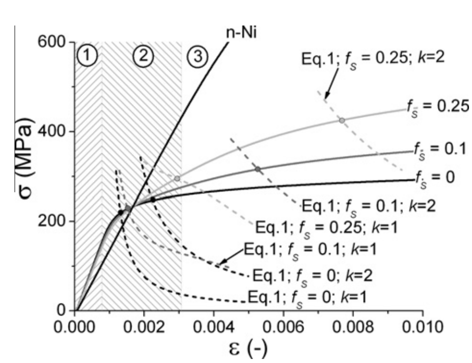

Figure 1. Evaluation of critical strength for an n-Ni/steel column with core slenderness ratio $L/r_C = 55$, sleeve area fractions $f_S = 0$, 0.1 and 0.25, and end constraints $k = 1$ and 2, showing the average stress $\sigma(\varepsilon) = \sigma_S(\varepsilon)f_S + \sigma_C(\varepsilon)(1 - f_S)$ (identified by the value of f_S), and the inelastic version of Eq. (1) for each k and f_S.

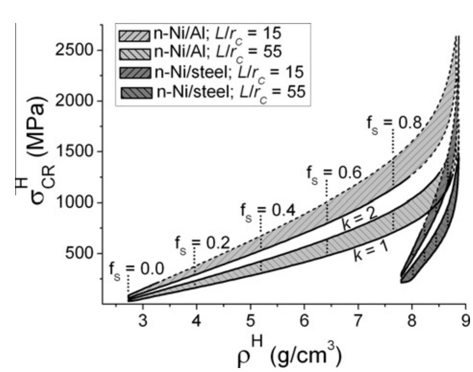

Figure 2. Critical stress (σ_{CR})–density (ρ) envelopes of n-Ni/Al and n-Ni/steel columns with core slenderness ratios $L/r_C = 15$ and 55 and $0 \leqslant f_S \leqslant 0.9$, showing the $k = 1$ and $k = 2$ lower and upper bounds, and critical stress where the compressive stress in the sleeve is lower than the tensile stress of the material (solid lines).