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Designing laminated metal composites for tensile ductility

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ABSTRACT

This contribution draws practical implications of a recently published estimation of the tensile ductility in laminated composites made of two ductile materials, typically metals or alloys, which harden as both the strain and the strain-rate increase. To this end, the literature is surveyed to collect values for the strain hardening exponent, the strain-rate sensitivity and the strength constant for a wide range of engineering metals and alloys. Material combinations that might produce ductile laminated metal composites are then examined in light of the data and theory. A simple graph is proposed, which gives a direct reading of the predicted elongation to failure of composites containing equal volume fractions of any two materials among those surveyed. The resulting plots show material combinations in which a more ductile material can significantly increase, within a laminated metal composite (LMC), the tensile elongation of a less ductile material. In this role, 304 stainless steel and commercial purity iron emerge as sensible possibilities.

1. Introduction

Of the many variables that govern the tensile elongation of ductile materials, strain-rate hardening is that which exerts the most dramatic influence: even small increases in a ductile material's strain-rate parameter m can strongly increase its tensile elongation; very high m values, roughly above 0.3, will even make it superplastic. How strain-rate hardening increases the elongation of materials is not simple: it does so, not by delaying the onset of instability (as work hardening does), but by retarding the consequences of necking. This makes the effect visible in experimental data: a typical signature of elongation driven by strain-rate hardening is the presence, in tensile stress–strain curves, of a long stage of deformation after the applied load has peaked [1–4]. This feature of the influence exerted by strain-rate hardening on tensile ductility complicates its analysis because one must examine the course of events beyond the onset of instability, at which a neck starts elongating faster than the remainder of a tensile bar. Linear stability analysis is then essentially useless, a fact that was identified and explained by Hutchinson and co-workers [1,4], who simultaneously with Ghosh [3] proposed a non-linear analysis of the deformation of strain-rate sensitive tensile bars under what is known as the long-wavelength approximation. This separates the bar in two collinear regions, one slightly thinner than the other, and then integrates their collective deformation behaviour assuming uniform tensile stress across any section normal to the applied load. These assumptions make the problem tractable using simple numerical methods, and show how strain-rate sensitivity delays the transition to unstable thinning of the thinner portion in this two-zone description of a necked tensile bar.

In a recent paper, this analysis was extended to tackle, in general terms, the uniaxial tensile deformation of equistrain composites (*e.g.*, laminated composites stressed along their plane of lamination, or fibre composites stressed along their axis) made of two strongly bonded work hardening and strain-rate sensitive ductile materials (generally, but not necessarily, of metal) [5]. To distinguish these from the composite material, each of these two bonded materials making the composite is called a "phase" in what follows, even though these might, by themselves, be multiphased. Here, practical implications of the analysis are examined, to probe how it can aid the design of ductile laminated metal composites (LMCs), originally reviewed by Sherby, Wadsworth et al. [6,7], more recent reviews being in Refs. [8–10]. This is done by gleaning literature data for the governing parameters K, n and m of a variety of metals and alloys, and then using these as input to identify combinations that might (or might not) hold promise for the design of ductile metallic LMCs. The article begins with a brief overview of the model, and then turns to its use and its implications.

2. Governing equations

Consider a composite made of two components: A (a ductile phase) and B (a less ductile phase), Fig. 1. The two are strongly

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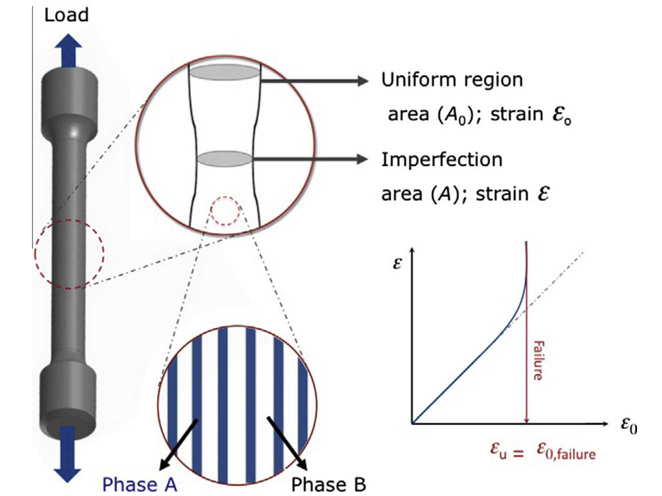

Fig. 1. Sketch of a tensile bar of laminated metal composite, and of the geometry assumed in the long wavelength analysis.

bonded and resist delamination as the composite deforms. Parallel to the plane of lamination, the flow stress of layered composites can reasonably be assumed to obey the rule-of-mixtures:

$$\sigma_{LMC} = V_A\sigma_A + V_B\sigma_B \quad (1)$$

where σ_A and σ_B are respectively the stress in each of the two phases A or B when it is deformed to the average tensile strain of the composite, ε; the same rule of course applies also to aligned fibre composites pulled along the fibres. Parameters V_A and $V_B = 1-V_A$ are the volume fractions of Phases A and B respectively, and σ_{LMC} is the true (average) stress acting on the multilayered composite along the direction of applied stress. The two phases, A and B, are assumed to be distributed on a scale sufficiently fine that their stress and strain state always remain uniform across each cross-section of the composite normal to the stress axis, yet sufficiently large that their mechanical behaviour remain unaffected by plasticity size effects (so that data from bulk materials testing, reviewed below, can be used).

Following Hutchinson and Neale [1], the tensile specimen is assumed to have a uniform cross sectional area, exception made for a reduced (also called "non-uniform") section of cross-sectional area only a small fraction η smaller than the remaining, main "uniform" part of the same section. The long-wavelength assumption takes it that the transition to this reduced section is sufficiently gradual for the stress to be everywhere uniaxial. The gage section of the tensile bar is thus made of two colinear regions, one slightly wider and much longer than the other, the latter being of thinner cross section and destined to become the necking region of the tensile bar. Axial load equilibrium between the uniform and non-uniform portions dictates:

$$[V_A\sigma_A + V_B\sigma_B]A = [V_A\sigma_{A,0} + V_B\sigma_{B,0}]A_0 \quad (2)$$

where A and A_0 are the instantaneous cross-sectional areas of the reduced and uniform sections respectively, and all quantities associated with the uniform portion are denoted, in Eq. (2) and in all that follows, with a subscript 0. By definition, the initial fractional non-uniformity is:

$$\eta = \frac{A_{0,in} - A_{in}}{A_{0,in}} \quad (3)$$

with A_{in} and $A_{0,in}$ the initial cross sectional area of the reduced and uniform portions of the gauge section, respectively. Assuming constant volume, the true strain in the reduced (ε) and uniform (ε_0) portions of the considered sections is related to their cross-sectional areas (A, A_0) or lengths (L, L_0) by:

$$\varepsilon = -\ln\frac{A}{A_{in}} = \ln\frac{L}{L_{in}}, \quad \varepsilon_0 = -\ln\frac{A_0}{A_{0,in}} = \ln\frac{L_0}{L_{0,in}} \quad (4)$$

Combining Eqs. (3) and (4) with Eq. (2) leads to:

$$V_A\sigma_A + V_B\sigma_B = \frac{e^{\varepsilon-\varepsilon_0}}{1-\eta}[V_A\sigma_{A,0} + V_B\sigma_{B,0}] \quad (5)$$

To describe the time-dependent flow stress of the two phases making the laminate, a customary constitutional law is adopted, in which contributions from strain hardening and strain-rate hardening to the flow stress are added [1][3]:

$$\sigma = K\left[\varepsilon^n + m\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_R}\right)\right] \quad (6)$$

Here K is the strength constant, n the strain-hardening exponent, m the strain-rate hardening constant and $\dot{\varepsilon}_R$ a reference strain-rate, typically given by the value $5\times10^{-5}\,s^{-1}$ [3]. This description of the material's flow stress is convenient in the context of composites, as will be seen below. It also has a physical grounding, in that the strain-rate sensitivity m in Eq. (6) is directly related to the (measurable) activation volume V_a characteristic of the thermally activated event that governs the strain-rate dependence of plastic flow:

$$mK = \frac{MkT}{V_a} \quad (7)$$

where kT has the usual meaning. Writing Eq. (6) for the two phases A and B and inserting these two equations into Eq. (5) gives:

$$e^{-\varepsilon}\left[V_AK_A\varepsilon^{n_A} + V_BK_B\varepsilon^{n_B} + (V_AK_Am_A + V_BK_Bm_B)\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_R}\right)\right] = \frac{e^{-\varepsilon_0}}{1-\eta}\left[V_AK_A\varepsilon_0^{n_A} + V_BK_A\varepsilon_0^{n_B} + (V_AK_Am_A + V_BK_Bm_B)\ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}_R}\right)\right] \quad (8)$$

for the composite in the long-wave length assumption. Two dimensionless parameters then emerge:

$$\beta = \frac{V_AK_A}{V_AK_A + V_BK_B} \quad (9)$$

$$\mu = \beta m_A + (1-\beta)m_B \quad (10)$$

which, when inserted into Eq. (8), turn it into:

$$\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_R}\right) = \frac{e^{\varepsilon-\varepsilon_0}}{1-\eta}\left[\frac{\beta\varepsilon_0^{n_A} + (1-\beta)\varepsilon_0^{n_B}}{\mu} + \ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}_R}\right)\right] - \frac{\beta\varepsilon^{n_A} + (1-\beta)\varepsilon^{n_B}}{\mu} \quad (11)$$

This gives, for a given level of deformation (at which the uniform and reduced sections have respectively reached strains ε_0 and ε), the relation between instantaneous strain increments in the two regions of the tensile bar. Assuming then a fixed strain-rate in the uniform section of the tensile sample gage length (*i.e.*, that $\dot{\varepsilon}_0$ is constant), the deformation in the reduced section can be deduced by numerical integration across small time steps. At some point $\dot{\varepsilon}$ diverges rapidly to infinity: this is when the tensile bar breaks.

This succession of events is depicted in Fig. 1, which depicts a homogeneous composite of two finely divided continuous phases that are aligned along the axis of the tensile bar, such that the equistrain rule of mixtures applies everywhere. One region of the tensile bar is slightly narrower than the rest. The inhomogeneity being small, as the bar is pulled the two regions deform at first together, with strain in the imperfection only slightly higher than