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Superplasticity in Laminated Metal Composites

Don Lesuer
Chol Syn
Oleg Sherby

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Lawrence Livermore National Laboratory

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Don Lesuer, Chol Syn and Oleg Sherby

Lawrence Livermore National Laboratory
Livermore, CA 94551

Introduction

Several studies have shown the possibility of achieving superplastic behavior in laminated metal composites consisting of alternating layers of superplastic and non-superplastic materials. Achieving high rate sensitivity in such a laminate requires the appropriate choice of component materials and component volume fraction as well as deformation under appropriate conditions of strain rate and temperature. The first investigators to study this behavior were Snyder et al. [1], who demonstrated that a non-superplastic material (interstitial free iron) could be made superplastic by lamination with a superplastic material (fine-grained ultrahigh carbon steel (UHCS)). Other laminates in which superplasticity has been observed in a non-superplastic material include UHCS/stainless steel and UHCS/aluminum bronze. In these studies, tensile tests were conducted with the tensile axis parallel to the layers. High strain rate sensitivities were observed and are associated with high tensile ductilities. However, as observed by Tsai et al. [2], obtaining high strain rate sensitivity is a necessary but not sufficient condition for high elongations. Tsai et al. studied the UHCS/brass laminate and found that, despite a strain rate sensitivity exponent of 0.5, only about 60% elongation was obtained. The low tensile ductility resulted from brittle, intergranular fracture of the brass. Once cracking started in the brass, cracks penetrated into the UHCS and premature failure resulted. Thus high elongations requires achieving high strain rate sensitivity as well as avoiding brittle fracture in the less ductile layer. In addition to tension, other deformation modes, including compression [3] and co-extrusion [4], have been studied for deformation response under conditions of high strain rate sensitivity.

Mechanics of Superplastic Deformation in Laminates

The deformation behavior of a well-bonded laminate (for the tensile axis parallel to the layers) can be predicted assuming isostrain behavior. Calculations using such an approach can correctly predict the strain rate sensitivity of the laminate as well as the activation energy. Thus the flow stress of the laminate can be obtained from the following relation.

$$\sigma_{lam} = f_1\sigma_1 + f_2\sigma_2 \tag{1}$$

where f_1 and f_2 are the volume fractions of components 1 and 2, respectively, and σ_1 and σ_2 are the flow stresses for components 1 and 2, respectively. This relation can be used for calculating the σ-$\dot{\varepsilon}$ response of laminates as a function of temperature, volume fraction of the components and the σ-$\dot{\varepsilon}$ behavior of the component materials. The results can be used to evaluate the influence of these quantities on the strain rate sensitivity exponent (m) and expected flow behavior of the laminate.

In the present study, the $\dot{\varepsilon}$-σ behavior of the component materials, consisting of a superplastic material and a non-superplastic material, are represented with the following constitutive equation.

$$\dot{\varepsilon} = KD\left(\frac{\sigma}{E}\right)^n \tag{2}$$

where K is a constant, D is the diffusion coefficient and n=1/m (and m is the strain rate sensitivity exponent of the material).

For our analysis we consider a laminate consisting of a fine-grained superplastic UHCS material (UHCS-10Al-1.2C) and a mild steel. This alloy has been shown to exhibit a strain-rate-sensitivity that approaches unity (m = 1) at high temperatures and low strain rates. This deformation response results from a mechanism involving grain boundary sliding (GBS) which occurs at a rate determined by solute-drag-controlled dislocation glide (glide-controlled GBS). In this mechanism, the diffusion coefficient D is for the diffusion of aluminum in iron. At higher strain rates, the dominant deformation mechanism is solute-drag-controlled dislocation creep (glide-controlled dislocation creep), which produces a strain rate sensitivity exponent of 0.33. As with glide-controlled GBS, the value of D for glide-controlled dislocation creep is the diffusivity of aluminum in iron. Grain boundary sliding and glide-controlled dislocation creep are independent deformation processes and, therefore, the total strain rate ($\dot{\varepsilon}_{total}$) resulting from these two mechanisms can be taken as

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{dislocation\ creep} + \dot{\varepsilon}_{GBS} \quad (3)$$

where $\dot{\varepsilon}_{dislocation\ creep}$ is the strain rate from dislocation creep and $\dot{\varepsilon}_{GBS}$ is the strain rate from GBS. The other component of the laminate is mild steel, which deforms by climb-controlled dislocation creep. This deformation mechanism, which has a strain-rate-sensitivity exponent of 0.2 and a value of D equal to lattice diffusion (Fe in mild steel), is typically observed in coarse-grained materials at intermediate temperature. This deformation mechanism is the only one expected to be active in coarse-grained mild steel at the temperatures and strain rates of interest. The parameters for Equation (2) have been summarized in a recent publication [4].

The flow stress-strain rate response at 1323K for the component materials and a 50/50 laminate (50% UHCS and 50% mild steel) is shown in Fig. 1a. The results show that the flow stress-strain rate response of the laminate is strongly influenced by the stress-strain rate behavior of the stronger component (mild steel at low strain rates and the UHCS material at high strain rates). The UHCS-10Al-1.2C alloy shows the transition from GBS to slip creep at a strain rate of about 10^{-3} s^{-1}. The laminate shows the greatest strain rate sensitivity ($d \log \sigma$ / $d \log \dot{\varepsilon}$) at approximately the same strain rate (approaching m = 0.45). This is an important finding, since the uniformity of plastic flow is expected to increase with increasing strain-rate sensitivity.

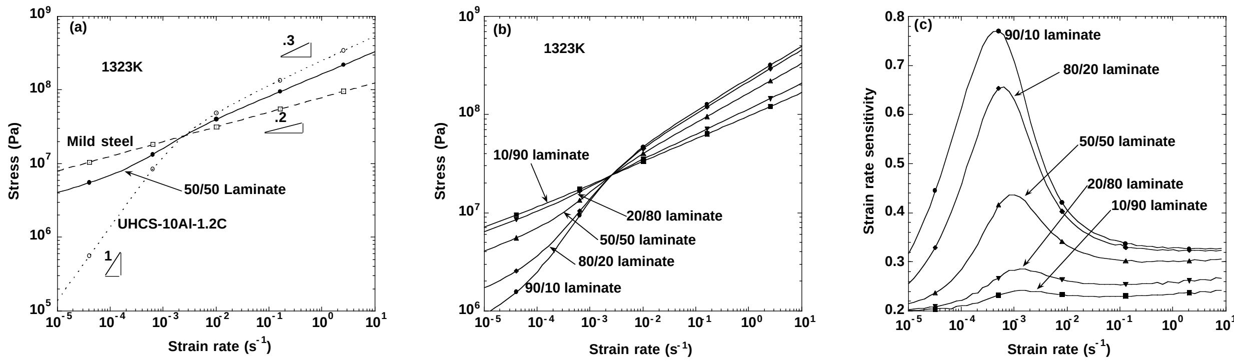

Fig. 1. (a.) Stress - strain rate behavior for the component materials in a laminate (UHCS-10Al-1.2C and mild steel) and a 50/50 laminate at 1323K. (b.) Influence of component material volume fraction on the stress - strain rate response. (c.) Strain rate sensitivity versus strain rate for the five laminates shown in Fig. 1b.

The influence of component volume fraction on stress- strain rate behavior is shown in Fig 1b for laminates containing 90%, 80%, 50%, 20% and 10% of the UHCS component. The resulting strain rate sensitivity as a function of strain rate is shown in Fig. 1c. These results show that high strain rate sensitivity exponents can be achieved in the laminate - exceeding m=0.7 in the 90/10 laminate, 0.6 in the 80/20 laminate and 0.4 in the 50/50 laminate over approximately one decade in strain rate. Thus a reasonable strain rate window exists for deforming these laminates under conditions of enhanced formability.

The results in Fig. 1 suggest that a critical condition must be met for high strain rate sensitivity in the laminate - namely, the harder component must exhibit high strain-rate-sensitivity. Recently, powder metallurgy processed and mechanically alloyed aluminum alloys have been found to be superplastic at high strain rates (between 10^{-2} and 100 s^{-1}) (references 1-4 in [5]) and thus offer the possibility for enhancing formability during extrusion at the strain rates used in this study. Specifically, two mechanically alloyed aluminum alloys, IN9052 (Al-4Mg-1.1C-0.8) and IN9021 (Al-4.4Cu-2.0Mg-1.1C-0.8O), have shown strain rate sensitivity exponents of 0.3 at strain rates of 2 to approximately 100 s^{-1}. Thus these two alloys offer the possibility of improving formability of a non-superplastic aluminum at high deformation rates when laminated.

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References

[1] B. C. Snyder, J. Wadsworth, and O. D. Sherby, *Acta Metallurgica*, 32 (6), (1984), 919-932.

[2] H. C. Tsai, J. Wolfenstine, and O. D. Sherby, *Composites*, 22 (5), (1991), 373-379.

[3] D. W. Kum, “Strength and Mechanical Behavior of Ferrous Laminated Composites Based on Ultrahigh Carbon Steels,” Ph.D. Thesis, Stanford University, (1984).

[4] D. R. Lesuer, C. K. Syn, J. D. Whittenberger, and O. D. Sherby, submitted to *Journal of the Mechanics and Physics of Solids,* (1998).
[5] W. J. Kim, E. Taleff, and O. D. Sherby, *Scripta Metallurgica et Materialia*, 32 (10), (1995), 1625-1630.