Layer Thickness Effect on Ductile Tensile Fracture of Ultrahigh Carbon Steel-Brass Laminates

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Laminated metal composites containing equal volume percentage of ultrahigh carbon steel (UHCS) and brass were prepared in three different layer thicknesses (750, 200, and 50 μm) by press-bonding and rolling at elevated temperature and were tensile tested at ambient temperature. A dramatic increase in tensile ductility (from 13 to 21 to 60 pct) and a decrease in delamination tendency at the UHCS-brass interfaces were observed as the layer thickness was decreased. The layer thickness effect on ductility is attributed to residual stress whose influence on delamination is decreased as the layer thickness is decreased. Suppression of delamination inhibits neck formation in the UHCS layers, allowing for extended uniform plasticity. For a given layer thickness, the tensile ductility decreases as the ratio of hardness of component layers is increased.

I. INTRODUCTION

LAMINATED metal composites are rarely considered for structural applications in contemporary engineering materials even though they have had an ancient history, e.g., welded damascus steels.[1] Nevertheless, there are compelling reasons to consider the potential of such materials for specific applications. Both fracture toughness and tensile ductility can be enhanced by lamination in a composite containing metal-metal layers. Fracture toughness, which is a measure of resistance to crack propagation, is improved by interlayer delamination, because the propagating crack is blunted or eliminated.[2,3] On the other hand, the tensile ductility, which is a measure of the extent of plastic flow, is degraded by delamination, because upon delamination, the hard component of the laminate will be free to neck and fracture soon thereafter.

Laminated materials based on ceramic-metal systems have been studied by a number of investigators.[4] In these cases, the fracture toughness is shown to be improved by lamination even though the ceramic component exhibits no plastic flow within itself. This is different from metal-metal composites where significant plasticity is obtained in all layers even when there is a large difference in ductility for the individual layers.

The influence of layer thickness on mechanical properties of multilayered composites has been rarely investigated. Studies have been made on polymer-based laminated composites, where it was shown that the fracture strength of the laminate was increased as the layer thickness was decreased.[5] Other studies have been done on microlaminates based on copper and nickel, where a layer thickness effect on fracture strength was observed in the thickness range of a few micrometers to a few nanometers.[6,7]

The purpose of this article is to present some results on the influence of layer thickness on the tensile ductility and fracture behavior of laminated metal composites (LMCs) based on ultrahigh carbon steel (UHCS) and brass. Earlier studies on UHCS-based laminated composites have centered on impact properties,[3] fracture behavior[8] and toughness[9] superplasticity[10,11] as well as tensile and bend ductility characteristics.[8,11,12]

II. EXPERIMENTAL DETAILS

A. Materials

Laminated metal composites containing equal volume percentage UHCS and brass were prepared in three different layer thicknesses, 750, 200, and 50 μm. The UHCS material used in preparation of the 50-μm layer laminates contained 1.25 wt pct C, 1.6 wt pct Al, 1.5 wt pct Cr, 0.5 wt pct Mn, and balance iron, while the UHCS material for the 750- and 200-μm layer laminates contained 1.8 wt pct C but the same composition otherwise. The UHCS materials were preprocessed by a hot- and warm-rolling technique[13] in order to achieve a fine ferrite grain size containing spheroidized carbide particles. The UHCS-1.25 wt pct C material exhibited a ferrite grain size of about 2 μm, whereas the UHCS-1.8 wt pct C material exhibited a ferrite grain size of about 0.5 μm.

The A1 transformation temperature for both UHCS materials was 770 °C. The brass was a commercial “cartridge brass” with a nominal composition of 70 wt pct Cu and 30 wt pct Zn.

B. Processing and Sample Preparation

Laminates were processed by press-bonding alone or press-bonding and rolling as described in detail elsewhere,[9,14] and the processing steps are summarized in Table I. Flat tensile test specimens in two orientations, “parallel” and “normal,” were prepared from the 750- and 200-μm layer laminates. Specimens of the parallel orientation were cut out such that the layers were parallel to the tensile axis and to the flat face of the laminate; specimens of the normal orientation were machined so that the tensile axis was normal to the layers. Only parallel specimens were made from the 50-μm layer laminate. Prior to machining of the tensile specimens, different
Table I. Processing of UHCS-Brass Laminates of Different Layer Thicknesses

<table>
<thead>
<tr>
<th>Final Layer Thickness</th>
<th>Processing Step</th>
<th>Processing Method</th>
<th>Temperature (°C)</th>
<th>Reduction Ratio</th>
<th>Total Reduction Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 μm</td>
<td>1</td>
<td>PB*</td>
<td>750</td>
<td>4:1</td>
<td>4:1</td>
</tr>
<tr>
<td>200 μm</td>
<td>1</td>
<td>PB</td>
<td>750</td>
<td>4:1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>PB</td>
<td>750</td>
<td>4:1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>R**</td>
<td>730</td>
<td>2.6:1</td>
<td></td>
</tr>
<tr>
<td>50 μm</td>
<td>1</td>
<td>PB</td>
<td>650</td>
<td>2.7:1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>R</td>
<td>700</td>
<td>2.3:1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>R</td>
<td>700</td>
<td>2.9:1</td>
<td>47:1</td>
</tr>
</tbody>
</table>

*PB: press-bonding
**R: rolling

heat treatments were performed on the 50-μm layer laminate to induce different microstructures in the UHCS layers. In all cases, no interdiffusion was observed between UHCS and brass layers, resulting in sharp and discrete boundaries, as shown elsewhere.^[8,9]^ 

C. Tensile Tests and Metallography

Tensile specimens were tested using an Instron machine at an engineering strain rate of $4 \times 10^{-4}$ s⁻¹. Samples were typically 2.5-mm thick and 5.0-mm wide with a uniform gage length of 12.5 mm. Microhardness measurements of the UHCS and brass layers were made using a Vickers indenter with a 100-g load. The microstructure was examined before and after testing using optical microscopy and scanning electron microscopy (SEM). The fracture surface was ultrasonically cleaned after tensile testing and examined using SEM.

III. RESULTS AND DISCUSSION

A. Tensile Flow Behavior

The tensile true stress-engineering strain curves for the laminates of three different layer thicknesses for the parallel tensile orientation are shown in Figure 1. The 750- and 200-μm layer laminates show about the same yield strength ($\sigma_y = 460$ MPa), whereas the 50-μm layer laminate shows a lower yield strength ($\sigma_y = 340$ MPa). This difference is mainly due to the higher carbon content in the UHCS material used in the two thick layer laminates, which led to a finer grain size and consequently a stronger material. The principal observation to be noted in Figure 1, however, is that the tensile ductility is dramatically increased as the layer thickness is decreased. The tensile ductility, in percent elongation, is 13 pct for the 750-μm, 21 pct for the 200-μm, and 60 pct for the 50-μm layer laminate.

Figure 2 shows the influence of layer thickness on the tensile ductility of the UHCS/brass laminated composite tested in the parallel orientation (Figure 1). The dashed line shown in the Figure 2 is the calculated average value, given as 35 pct elongation based on brass having a typical elongation of 60 pct[^14] and UHCS having a typical elongation of 10 pct.^[9,14] The trend shown in Figure 2 would suggest that the average prediction is only valid when the layer thickness is 100 μm. One interpretation