TENSILE BEHAVIORS OF ALUMINIUM - SELF REINFORCED POLYPROPYLENE FIBER METAL LAMINATES BASED ON 2/1 AND 3/2 CONFIGURATIONS

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ABSTRACT

Tensile behaviors of aluminum – self reinforced polypropylene fiber metal laminates (Al-SRPP FMLs) based on 2/1 and 3/2 configurations were investigated at various temperatures. The stress-strain curves of 2/1 and 3/2 Al-SRPP FMLs decline as the temperature improved while the ductility is enhanced. The elevated temperature intensifies the delamination of the Al-SRPP FMLs. The outer metal cracks and inter-laminar delamination are the main tensile failure mechanism for both the 2/1 and 3/2 Al-SRPP FMLs tested.

1.INTRODUCTION

Fiber metal laminates (FMLs) consisted of alternating metals and fiber-reinforced composites are successfully applied in aerospace and defense because of their excellent impact and fatigue characteristics as well as superior specific strength and stiffness [1]. Now the FMLs are finding applications in a serious of new areas such as automotive, rail transit and marine sectors [2]. The properties of FMLs are mainly determined by the properties of the individual layers (plies) and the stacking order [3]. The constituents of the laminates and the layered structure result in failure modes, unusual from monolithic materials like aluminum alloys [4].

P. Compston and W. J. Cantwell [5] developed a new-typed FMLs composed of thin layers of aluminum alloy and a thermoplastic fiber-reinforced polypropylene composite (termed a self-reinforced
polypropylene (SRPP). J.G. Carrillo [2] investigated the mechanical properties of the Al-SRPP FMLs. The paper utilized a modified polypropylene film to bond the aluminum–SRPP resulting in excellent interfacial adhesion. A range of tensile tests at room temperature showed that the FMLs offer a higher strength than that of the plain thermoplastic composite.

There are some investigations on mechanical properties of Metal-Polymer laminates (MPs), which contain polymers cores as interlayers. For examples, M. Weiss et al. [6] studied the influence of temperature on the mechanical properties of Aluminum/Polypropylene/Aluminum (APA) laminates. The results showed that the change in visco-elastic-plastic properties of the core material over the temperature are significant, but this only has a minor influence on the tensile properties of the APA laminates. The core thickness has a significant effect on the tensile properties of the Steel/Polymer/Steel sandwich materials (SMs) [7]. The yield strength (YS) and the ultimate tensile strength (UTS) as well as the Young’s modulus (E) decline with increasing the thickness of the polymer core. The aim of the present work is to investigate the mechanical behaviors of Al-SRPP FMLs under uniaxial tension at different heating temperatures conditions based on their configurations.

2. EXPERIMENTAL PROCEDURE

2.1. Materials and manufacturing procedure of the FMLs

The aluminum alloy 5083-H32 sheet with 0.3 mm thickness was used in this research as the metal layer and the chemical compositions are shown in Table 1. The composites layer consisted of one 0.4 mm thick SRPP (Curv®, Propex). Table 2 summarizes the mechanical properties of the 5083-H32 skin and the SRPP core. A modified ethylene-vinyl acetate copolymer (EVA) film with a thickness of approximately 50 μm, was embedded between the aluminum alloy and the SRPP as an adhesive. The aluminum alloy surface was pretreated with degreasing with alcohol, alkali cleaning, acid cleaning and anodizing in a phosphoric acid electrolyte in sequence prior to hot pressing. The FMLs were manufactured by stacking the SRPP, the adhesive film as well as the aluminum alloy together as the laminating configuration shown in Figure 1.

Tab 1. Chemical composition of 5083-H32 (w%).

<table>
<thead>
<tr>
<th>Si</th>
<th>Fe</th>
<th>Mg</th>
<th>Zn</th>
<th>Mn</th>
<th>Ti</th>
<th>Cr</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>0.16</td>
<td>4.50</td>
<td>0.12</td>
<td>0.61</td>
<td>0.10</td>
<td>0.10</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Tab. 2. Mechanical properties of 5083-H32 and SRPP at the room temperature.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Tensile Strength/MPa</th>
<th>Elongation/%</th>
<th>E-Module/GPa</th>
<th>Density/g·cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>5083-H32</td>
<td>420.0</td>
<td>8.33</td>
<td>75.4</td>
<td>2.68</td>
</tr>
<tr>
<td>SRPP</td>
<td>140.0</td>
<td>17.00</td>
<td>3.0</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Figure 1: Schematic view of the stacking arrangement of Al-SRPP FMLs: laminates of (a) 2/1 configurations, laminates of (b) 3/2 configurations.

Figure 2 illustrates the fabrication of Al-SRPP FMLs by hot-pressing. The three components of 250 mm by 250 mm were placed in a flat mould then were put in the plate vulcanizing machine and heated to 145°C [8]. This temperature is sufficient to melt the adhesive film without degrading the oriented polypropylene fibers in the SRPP [9]. A thermocouple was arranged for monitoring the temperature inside the mould. Once the temperature was achieved, a pressure of 0.4 MPa was applied for 5 mins after which the laminate was rapidly taken out and cooled in the air. Laminate configuration of 2/1 or 3/2 was achieved. The specifications of Al/SRPP FMLs based on 2/1 and 3/2 configurations are summarized in Table 3.

![Hot-pressing curves of the 2/1 and 3/2 Al-SRPP FMLs](image)

Figure 2: Hot-pressing curves of the 2/1 and 3/2 Al-SRPP FMLs

### Table 3. The specifications of Al/SRPP FMLs

<table>
<thead>
<tr>
<th>Samples</th>
<th>Skin layers</th>
<th>Interlayer</th>
<th>Adhesive layer</th>
<th>Adhesive layer</th>
<th>MVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al/SRPP-2/1</td>
<td>5083-H32(0.30mm)</td>
<td>SRPP(0.40mm)</td>
<td>EVA (50μm)</td>
<td>1.10mm</td>
<td>0.545</td>
</tr>
<tr>
<td>Al/SRPP-3/2</td>
<td>5083-H32(0.30mm)</td>
<td>SRPP(0.40mm)</td>
<td>EVA (50μm)</td>
<td>1.90mm</td>
<td>0.474</td>
</tr>
</tbody>
</table>

*MVF: metal volume fraction

2.2. Uniaxial tensile tests

For the tensile test, the laminates were sectioned into 200 mm × 15 mm strips along the rolling direction by water jet cutting. Burrs were removed from the edge of the strips using metallographic abrasive papers. The tensile tests were conducted at room temperature, 80°C and 145°C at a constant cross-head speed of 2 mm/min until fracture occurred on an Instron 5982 universal test machine with a
heating environmental chamber according to the ASTM D3039 testing standard (2000). True stress values are more accurate measures of stress than engineering values for large deformations, as is the true stress values when compared with engineering stress [10-11]. The true stress ($S$) and strain ($\varepsilon$) can be expressed by the following equation [12]:

$$S = \frac{F}{A} = \sigma_0 (1 + \varepsilon)$$ \hspace{1cm} (1)

$$\varepsilon = \ln \frac{l}{l_0} = = \ln(1 + \varepsilon)$$ \hspace{1cm} (2)

where $F$, $A$, $l$ and $l_0$ refer to the applied load, the instantaneous cross-sectional area, the instantaneous gage length and the initial length of the tested sample, respectively. Whereas $\sigma_0$ and $\varepsilon$ is the engineering stress and the engineering strain respectively.

3. RESULTS AND DISCUSSIONS

Figure 3 shows the stress–strain curve for the Al/SRPP-2/1 based on the tensile test standard. As can be clearly shown, the true stress-strain curve declines noticeably as the temperature rises and that means the strength decreases with increasing the test temperature. It is worth noting that the strain to failure are enhanced when the temperature is improved. The tested results above determined at elevated temperature could therefore be a result of the softening of the core material and metal skins as heated. A large increasement in strain occurs with the temperature changing from 80°C to 145°C for the Al/SRPP-2/1. In contrast to that, only minor enhancement in true strain value is observed between room temperature (RT) and 60°C for the Al/SRPP-2/1.

![Figure 3. Effective stress-strain curves derived from tensile tests at different temperatures: laminates of (a) 2/1 configurations.](image-url)
Whereas for the Al/SRPP-3/2, seen in Figure 4, the slope of the stress–strain curve diminishes dramatically at 80°C and 145°C. Compared to the Al/SRPP-2/1, the strain to failure of the Al/SRPP-3/2 is elevated more equably as the temperature is improved. The microscope examination through the thickness direction of the Al/SRPP-3/2 after the tensile tests at 80°C (Figure 4 (i)) and 145°C (Figure 4 (ii)) discovers the occurrence of plastic elongation only of the two outer metal skins. This implies that the ductility behaviours of the Al/SRPP-3/2 stress–strain curves is mainly caused by the plastic elongation of the two outer metal skins. As a consequence, the calculated slope of the stress–strain curve of the Al/SRPP-3/2 at 80°C and 145°C is smaller than the slope value at room temperature according to the equation (1). Figure 4 (i) and Figure 4 (ii) show that the plastic elongation value of the outer metal skins tested at 145°C is greater than the value tested at 80°C, which can be confirmed by the stress–strain curves of the Al/SRPP-3/2 at 80°C and 145°C in Figure 4. This could be related to the delamination of the laminate caused by the high temperature. The interfacial debonding contributes to the two outer metal skins deform relative to the inner composites layers under the action of clamping force. The interface state performs worse when the configuration of the Al/SRPP FMLs changes from 2/1 configuration to 3/2 configuration.

Because of the interfacial debonding of the Al/SRPP-3/2 at 80°C and 145°C, the integrality of the laminates is destroyed. Therefore, the mechanical performance values of Al/SRPP-3/2 at 80°C and 145°C will not be discussed in the following.

Figure 5 shows the yield strengths(YS) of the Al/SRPP-2/1 and Al/SRPP-3/2 tested at different temperatures. As the temperature rises, the YS of Al/SRPP-2/1 decreases slightly. As the figure shown, the YS value declines 2.0% approximately when the temperature climbs from room temperature to 80°C. However, when the temperature continues increasing to 145°C, the YS value decreases 9.4% nearly comparing to the YS at room temperature. This may be connected with the softening degree of the SRPP layers. In addition, the results indicate that the YS of Al/SRPP-2/1 is greater than the YS of Al/SRPP-3/2.
In Figure 6, it can be observed that the tensile strengths at fracture (TS) of the Al/SRPP-2/1 and Al/SRPP-3/2 at various test temperatures present regular changes similar to the yield strengths. In contrast with TS value at room temperature, TS value diminishes 9.1% and 24.4% tested at 80°C and 145°C, respectively. The results demonstrate that the TS values of the Al/SRPP-2/1 and Al/SRPP-3/2 at room temperature follow the rule of mixture for flow stresses of the laminate sheets. Equation (3) gives the proportion, where $\sigma$ and $V$ indicate the uniaxial flow stress and volume fraction, and subscripts $LS$, $M$ and $C$ represent the laminate sheets and its layers “$M$” metal and “$C$” composites, respectively [13]. Meanwhile it confirms that the TS of Al/SRPP-2/1 is superior to the TS of Al/SRPP-3/2.

\[
\sigma_{LS} = \frac{\sigma_M \cdot V_M + \sigma_C \cdot V_C}{V_M + V_C}
\]  

(3)
In order to gain more information about the tensile failure of the Al/SRPP FMLs, scanning electron microscopy (SEM) was performed on cross-sections of the fracture for the Al/SRPP-2/1 and Al/SRPP-3/2 after the tensile tests. Figure 7a shows that a piece of the outer metals of the Al/SRPP-2/1 ruptures under the tension, while the SRPP layer bears no obvious damage. Simultaneously, delaminations occur at the metal/composite interface in the vicinity of the fracture. The tensile strengths of the 5083-H32 is 2.4 times greater than corresponding value of the SRPP (presented in Tab.2). It thus appears that the tensile stress that the outer metal skins beared is greater than or equal to the SRPP layer bears during the tensile tests. When the tensile temperature increases, seen in Figure 7b and 7c, the Al/SRPP-2/1 exhibit a similar failure as the Figure 7a shows. However, delaminations between the outer metal and the SRPP layer are severe as the temperature rises to 145°C. It indicates that higher tensile temperature for a Al/SRPP-2/1 has an adverse effect on its interfacial bond property. Compared with the Al/SRPP-2/1 tested at room temperature (Figure 7a), except for the similar crack of the outer metal skins, the Al/SRPP-3/2 exhibits extensive debonding between the outer metal and the SRPP layer extending from the crack center (seen in Figure 7d). Figure 7e and 7f shows the most severe interlayer delaminations of Al/SRPP-3/2 occurred at 80°C and 145°C separately. It also proves the general failure of Al/SRPP-3/2.

4. CONCLUSIONS

The results showed that the tensile behaviors of the Al-SRPP FMLs are distinguishable at different temperatures. The stress values of both 2/1 and 3/2 Al-SRPP FMLs significantly decreased with the increase of temperature. On contrast, elevated temperatures led to an increased ductility of the laminates. Due to the surface slippage caused by the tensile plastic deformation only of the two outer metal skins, the calculated elasticity modulus of the 3/2 Al-SRPP FMLs configurations at 80°C and 145°C were smaller than the elasticity modulus value at room temperature. The tensile stress that the outer metal skins of the Al-SRPP FMLs beared is greater than or equal to the Al-SRPP FMLs core materials beared during the tensile tests at room temperature, 80°C and 145°C.
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