THERMAL SHOCK CRACKING BEHAVIORS OF 2D WOVEN CARBON FIBER REINFORCED MAGNESIUM MATRIX COMPOSITE

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1 Introduction

Carbon fiber reinforced magnesium (C/Mg) matrix composites offer interesting opportunities in terms of specific strength and modulus with proper electrical conductivities and advantageous thermal properties, which make them an excellent material for various engineering applications such as robotic high-precision machining tools, positioning systems, textile techniques, high-performance electronics, aerospace and high precision space-based systems [1-3].

Previous studies showed that extremely high strength, modulus and near-zero coefficient of thermal expansion (CTE) values can be reached by the reinforcement of magnesium with unidirectional carbon long fibers [1]. This is partially true only for their properties in axial fiber direction, while their properties in transverse fiber direction are unacceptably low for engineering applications [4]. In this reason, unidirectional composites are not normally used solely for the structural components; multidirectional composite laminates, which consisted of unidirectional composite layers with different fiber orientations, are much suitable for various stress environments [5].

On the other hand, composite parts for aeronautic and aerospace industries experience periodical temperature fluctuations between low and high temperature due to their high service temperature. For example, a satellite in a low-earth orbit passes in and out of the earth’s shadow during operation, which can cause thermal cycles between temperatures of -100°C and 100°C. These transient thermal conditions, together with the anisotropic CTE values of each unidirectional composite layer, cause strain misfit and large internal thermal stresses at interfaces between layers in composite laminates. These interfacial thermal stresses reduce thermal fatigue resistance and often provide the source of failure such as thermal shock cracking and significant thermal degradation during thermal cycling [6]. Composite laminates made of unidirectional layers are highly susceptible to thermal shock damage because of the highly anisotropic properties and low transverse strength of each composite layer.

It has been observed that one of the most detrimental damage in fiber reinforced laminates caused by cyclic thermal loading is delamination between the layers, which can considerably reduce the in-plane compressive strength of the laminates [7]. One of the ways of overcoming these problems is to use woven fabric layers instead of unidirectional layers. A woven fabric is a fabric produced by the process of weaving in which the fabric is formed by interlacing the warp and fill strands. The integrated natures of the fabric offer balanced properties in the warp and fill directions. Due to the interlacing of fiber tows in tow directions, woven fabric composites offer better damage tolerance as compared to unidirectional composites.

This study focuses on the effect of temperature fluctuations on the microstructure and in-plane compressive strength of 2D woven C/Mg composite laminate. Plain woven carbon fabric reinforced magnesium matrix composite laminates were fabricated by pressure infiltration method, and their thermal shock behaviors were investigated using simple quenching method of thermal shock test. The experimental results were also compared and contrasted with those from commonly used unidirectional C/Mg laminates.
2 Experimental Procedure

2.1 Materials

The materials used in this investigation were fabricated by a pressure infiltration casting process using a permanent metallic mold [8]. The matrix alloy was commercial AZ91 magnesium alloy (8.5-9.5%Al, 0.45-0.90%Zn, 0.15-0.30%Mn, 0.20%Si, 0.01%Ni and balance Mg), and the reinforcement was high-modulus carbon long fibers with a diameter of 10 μm. Two different quasi-isotropic C/Mg composite laminates with a volumetric fiber content of 60% were fabricated. They can be characterized as follows:

1. UD laminate: unidirectional C/Mg layers with a stacking sequence of [0, 45, -45, 90]_s (Fig.1a).
2. Woven laminate: woven C/Mg layers with a stacking sequence of [0, 45] (55 plies) (Fig.1b).

2.2 Thermal shock test

A simple quenching method of thermal shock test was carried out for the investigation. For the test, the laminates were machined and polished to cubic shapes with a length of 10mm. During each cycle, heating of specimens was achieved by electric furnace under argon atmosphere for 10 min. And cooling of specimens was achieved by quenching of the specimen until 50 cycles. The cooling time was 10 seconds for each cycle, in water at 25°C. The temperature range of the thermal shock test was selected to 225°C, as similarly to the operation temperature for their potential use in aeronautic and aerospace applications. The formation and extension behaviors of thermal shock induced cracks were studied by scanning electron microscope (SEM). To investigate the effect of thermal shock damage on the thermal degradation behaviors of the laminates, in-plain compressive tests were carried out for the laminate samples in as-cast state and after selected thermal cycles.

3 Results and Discussions

Fig.1 shows the schematics and optical micrographs of the UD and woven C/Mg laminates. In both of the laminates no cracks or voids were observed in the
THERMAL SHOCK CRACKING BEHAVIORS OF 2D WOVEN CARBON FIBER REINFORCED MAGNESIUM MATRIX COMPOSITE microstructures, indicating that sound C/Mg composite laminates were obtained by the pressure infiltration process.

During the thermal shock test, main damages in the microstructure were observed in a form of thermal shock induced cracking of the laminates. Fig.2 shows SEM morphologies of the thermal shock induced cracks in the laminates after 30 thermal shock cycles. In the case of the UD laminates, delamination cracks were found during thermal shock tests at the interfaces between layers. The delamination cracks in the UD laminates were started from the edge of the samples after a few thermal cycles, and were continuously propagated along interfaces with increasing thermal shock cycles. In contrast, thermal shock induced cracks in the woven laminates were mainly formed at warp/fill yarn interfaces. These cracks extended through the warp/fill yarn cross-over surfaces between two perpendicular yarns, and tended to be arrested at the end of warp/fill interfaces (highlighted by black arrows in Fig.2b). Interconnections of individual cracks were not observed during thermal shock test of the woven laminates, indicating that a thermal shock reliability of the woven laminates is superior to that of the UD laminates.

Table 1 lists compressive fracture strengths of the laminates in as-cast state and after selected thermal cycles. The compressive strengths of both laminates were decreased with increasing number of thermal shock cycles, as expected. From the results in Table 1, it can be clearly seen that the thermal degradation is far less significant in the woven than in the UD laminates: whereas the compressive strength of the UD laminates was reduced to about 11% of as-cast state by 50 thermal cycles, while the strength of the woven laminates after 50 cycles was approximately 33% of the as-cast state. Moreover, it was found that even after 50 thermal shock cycles the compressive strength of the woven laminates remains quite high value of 171MPa, which is generally acceptable for use in most of structural applications.

Through the study of microstructure and mechanical properties of the laminates during thermal shock tests, it was found that weaved fiber yarns in the woven laminates was effective to prevent thermal shock induced delamination and thermal degradation. The advantage of the woven laminates is attributed to the formation of the small cracks at warp/fill interfaces. This fact is beneficial in preventing delamination fracture effectively, since this type of cracks tends to be arrested at the end of warp/fill interfaces. Among two types of laminates which tested in this study, woven laminates may have good advantage to give a longer failure life under thermal shock environment. It is therefore sufficient to conclude that the woven laminates are more suited than UD laminates to the applications where a resistance to thermal shock damage is important, such as aeronautic and aerospace applications.

Table 1. Evolutions of compressive fracture strength of UD and woven laminates with thermal shock cycles.

<table>
<thead>
<tr>
<th>Cycles (N)</th>
<th>0 (as-cast)</th>
<th>15</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD</td>
<td>188±20</td>
<td>98±27</td>
<td>54±24</td>
<td>21±18</td>
</tr>
<tr>
<td>Woven</td>
<td>518±34</td>
<td>261±21</td>
<td>137±38</td>
<td>171±41</td>
</tr>
</tbody>
</table>

Fig.2. SEM micrograph of thermal shock induced cracks after 30 cycles in (a) UD and (b) woven C/Mg laminates.
4 Summary and Conclusions

In this study, UD and woven C/Mg composite laminates were fabricated by pressure infiltration method, and their thermal shock behaviors were investigated using simple quenching of thermal shock test. The results can be summarized as follows:

1. During the thermal shock test, main damages were observed in forms of thermal shock induced cracking in microstructures of both laminates. In the case of UD laminates delamination cracks were developed at the interfaces between layers, while thermal shock induced cracks in the woven laminates were mainly formed at warp/fill yarn interfaces.

2. The compressive strengths of both laminates were decreased with increasing number of thermal shock cycles. The compressive strength of the UD laminates was reduced to about 11% of as-cast state by 50 thermal cycles, while the strength of the woven laminates after 50 cycles was approximately 33% of the as-cast state.

3. After 50 thermal shock cycles the compressive strength of the UD laminates were unacceptably low for general engineering purpose. In contrast, the strength of woven laminates remains quite high value of 171MPa, which is generally acceptable for use in most of structural applications.

4. It was found that weaved fiber yarns in the woven laminates was effective to prevent thermal shock induced delamination and thermal degradation. This might be due to the fact that thermally induced cracks in the woven laminates are tended to be arrested at warp/fill interfaces. This crack extension behavior was confirmed by observing the microstructures of the tested samples. It was noted that the woven C/Mg laminates offered improved thermal shock resistance, and therefore would be beneficial for aeronautic and aerospace applications.

References


