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Analytical and numerical residual stress models for fiber metal laminates – comparison and application

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Abstract

Fiber metal laminates (FML) consist of alternately stacked plies of polymer matrix composites and metallic foils. Such material systems exhibit advantageous properties regarding fracture toughness, impact resistance and structural strength. Glass fiber reinforced aluminum (GLARE) with the constituents glass fibers, epoxy resin and aluminum foils is state-of-the-art. To improve the processing of FML thermoplastic matrix systems are promising. Carbon fibers could enhance the stiffness of the laminates. However, both modifications have a serious influence on thermal residual stresses grown by the mismatch of coefficient of thermal expansion and the cooling down from processing temperature. Finite element analysis (FEA) provides a reliable tool to predict the state of thermal residual stresses for FML made of different constituents. Otherwise, analytical models are an under-estimated but powerful tool, too. Closed formulas based on mechanical relationships can be applied fast and easy. Both, numerical and analytical methods are used to analyze thermal residual stresses caused by processing of different material systems.

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Keywords: fibre metal laminates; thermal residual stresses; modelling; processing

1. Introduction

Fiber metal laminates (FML) are hybrid material systems combining the advantages of metals and fiber reinforced polymers. A strong bonding of several layers of both materials provides integrity along with ductility from the metal and fatigue resistance from the composite part. A well-known and good understood

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FML is glass fiber reinforced aluminum (GLARE®). Impact resistance, crack growth behavior and other properties of this material are excellent as documented e.g. by Vlot, 2001 or Asundi 1997. However, drawbacks are the low stiffness and labor intensive manufacturing. Therefore, new material systems are under development to provide higher stiffness and a potential for higher automated production. To fulfill these requirements carbon fibers, thermoplastic matrices and stiffer metals are considered as constituents.

Using high performance thermoplastics require higher processing temperatures compared to the thermoset epoxy matrices used for GLARE. This leads to higher thermal residual stresses caused by cooling down from processing to ambient temperature. Furthermore, the coefficient of thermal expansion (CTE) of carbon fibers is very inappropriate concerning thermal residual stresses when combined with metals. Thermal residual stresses are superpositioned to the applied stresses leading to possibly premature failure of constituents. Additionally, pre-loading by residual stresses causes constant interlaminar shear stresses at the edges of the laminates and in the vicinity of cracks or holes. This may lead to premature delaminations.

To estimate the magnitude of thermal residual stresses analytical and numerical models can be used. This helps to evaluate different material combinations and to accelerate the development of promising material systems.

2. Material systems

Different material systems were considered in this study. The selection of the constituents was made with the aim to cover a wide range of material combinations. The most important properties influencing thermal residual stresses are CTE, young’s modulus and processing temperature along with fiber orientation and volume fraction of the constituents. These properties are influencing the thermal residual stresses directly. Indirect factors, e.g. consolidation pressure, post-processing heat treatments and relaxation processes, were not considered in the following analysis.

Figure 1 provides an overview on the polymers, fibers and metals which were considered, their basic properties and their influence on the thermal residual stress state. For the metallic part the aluminum alloy AA2024 T3, the β-titanium alloy 15-3-3-3 (Ti15-3), and the stainless steel CrNi18-10 are considered. The polymeric matrices under consideration are polyamide 66 (PA66), polyphenylensulfide (PPS), and polyetheretherketone (PEEK).

Fig. 1. Constituents, their main properties and their influence on thermal residual stresses
2.1. Properties

For the calculation of thermal residual stresses a linear and fully elastic material behavior was considered. This is allowed since the stress levels are low enough that no yielding especially in the metal part occurs. The properties of the fiber reinforced plastic lamina were derived by the rule of mixture. The fiber volume fraction has been considered as 60%. The lamina properties used for calculation are given in table 1.

Table 1. Properties of fiber reinforced plastic lamina used for calculation

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Carbon fiber (HM)</th>
<th>E-Glass fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix type</td>
<td>PA66</td>
<td>PPS</td>
</tr>
<tr>
<td>E-Modulus 1 [GPa]</td>
<td>175.0</td>
<td>175.1</td>
</tr>
<tr>
<td>E-Modulus 2 [GPa]</td>
<td>5.05</td>
<td>5.69</td>
</tr>
<tr>
<td>G-Modulus 12 [GPa]</td>
<td>2.97</td>
<td>3.24</td>
</tr>
<tr>
<td>G-Modulus 23 [GPa]</td>
<td>1.86</td>
<td>2.03</td>
</tr>
<tr>
<td>CTE 1 [ppm/K]</td>
<td>-0.1303</td>
<td>-0.1485</td>
</tr>
<tr>
<td>CTE 2 [ppm/K]</td>
<td>50.159</td>
<td>44.047</td>
</tr>
<tr>
<td>Poison ratio 12 [1]</td>
<td>0.240</td>
<td>0.264</td>
</tr>
</tbody>
</table>

2.2. Lay-up of the laminate

A generic laminate with two outer layers of metal sheets with 0.5 mm thickness each and an inner composite core with a thickness of 0.6 mm has been set-up. The composite core consists of four plies (0.15 mm each) with an orientation of +/- 22.5°. Thus, the fiber metal laminate has a total thickness of 1.6 mm. The fiber orientation was selected with the intention to obtain a preferred loading direction together with balanced properties in the other directions.

3. Thermal residual stresses

Thermoplastic fiber metal laminates are consolidated by hot pressing above the melting point of the matrix. It is assumed that processing induced thermal residual stresses are developing during cooling down from a stress free temperature to room temperature (20°C). The stress free temperature is assumed slightly below the solidification temperature of the matrix. Further effects such as viscosity of the matrix or relaxation by creeping were not considered.

3.1. Finite element analysis

The finite element analysis has been conducted by simulating the cooling down from solidification temperature of the thermoplastic matrix to room temperature using the FE-System Abaqus. The generic laminate with two outer layers of metal sheets and a composite core as described in section 2.2. has been analysed.

The three-dimensional model in Abaqus was implemented with isotropic properties for the metal part and orthotropic properties for the volume elements representing the composite lamina. A perfect bonding of the
different layers has been assumed. The model was constrained by symmetric conditions at two edges and with free surfaces at the other two edges. Therefore, it represents a free corner of a large sheet.

3.2. Analytical approach

Due to the different CTE of metal and composite the layers are building up stresses with each temperature change. The overall sum of these stresses has to be zero when the FML is in the unloaded state. This boundary condition means that the forces of the layers need to be balanced. Thereby the following equation can be developed to estimate the thermal residual stress of the metal fraction $\sigma_M$:

$$
\sigma_M = \frac{\Delta T(\alpha_C - \alpha_M)}{\frac{E_C}{1 - v_C} + \frac{1}{E_M}}
$$

(1)

Where $\Delta T$ is the temperature difference to a stress free reference temperature (negative for cooling-down!), $\alpha_C$ and $\alpha_M$ are the CTE of composite and metal, respectively. $E_C$ and $E_M$ are the Young’s Modulus of composite and metal, respectively. $v_C$ is the volume fraction of the composite layers in relation to the overall thickness of the laminate.

The knowledge of $\sigma_M$ and the balance of forces allows to calculate the thermal residual stress of the composite $\sigma_C$ by:

$$
\sigma_C = -\frac{1 - v_C}{v_C} \cdot \sigma_M
$$

(2)

It needs to be mentioned that the input properties of the composite, i.e. $\alpha_C$ and $E_C$ are determined by the classical laminate theory under consideration of the +/-22.5° lay-up. The highest thermal residual stresses are expected in 0°-direction. Therefore, the stress levels were derived for this direction only.

4. Results

The thermal residual stresses in the composite and in the metal fraction determined by FEA are compared to the results determined by the analytical approach. Here the mean stresses in 0°- direction are considered. Fig. 2 (left) provides an overview of the results of titanium containing FML with different matrix and fiber types. As expected the stresses in the metal are tensile with their compressive counterparts in the composite. Furthermore, the stress levels when using carbon fibers are much higher compared to the glass fiber containing FML. The discrepancy of the FEA and analytical results is up to 20 MPa in the titanium.

Fig. 2 (right) provides a comparison of different metals. Here, the matrix is kept constant as PA66. The stress levels of the aluminum and steel containing FML are significantly higher than that of the titanium FML. Again, the fiber type has a drastic influence on the stress levels.
4.1. Discussion of results

The values of thermal residual stresses determined by FEA and analytically are at the same level. Discrepancies are caused by the interaction of multi-axial stresses and edge effects in the FEA which were not considered in the analytical approach.

In general, the stresses of glass fiber reinforced FML are at a moderate level. The combination with aluminum has the highest thermal residual stresses. In combination with the lowest strength of the metals investigated that could be critical. Due to the higher processing temperature the stresses are higher compared to GLARE®.

Since the titanium alloy has the lowest CTE and a relatively low Young’s modulus the stresses in titanium based FML are at the lowest level of the investigated systems. However, the stress level when using carbon fibers is still very high. It would be even higher in the metal part when the composite fraction will be increased as it will be the case in many technical relevant FML compositions.

Especially the high stiffness of steel generates a high level of thermal residual stresses. When using carbon fibers, it will be very difficult to handle a FML with such a high level of thermal residual stresses. Since the stresses in the metallic part are of tensile nature a further superposition of cyclic tensile loading results in a high susceptibility for fatigue cracks. Especially for aluminum/carbon fiber based laminates the thermal residual stresses are already above the fatigue limit of the alloy.
If FML with combinations of high levels of thermal residual stresses are used, different methods for reduction of these stress levels may be considered. Firstly, as described e.g. by Khan, et al., 2009 for FML or by the author for metal matrix composites (Hausmann, et al., 2004), a pre-stretching of the material leads to a reduction of the residual stress level. Secondly, a slight effect of stress reduction can be obtained by thermal post-treatments of FML as reported by Schulze et al., 2011. Thirdly, the level of thermal residual stresses can be influenced by the composite lay-up. It can be optimized for specific applications under consideration of internal stresses and applied loads.

5. Conclusions

Glass fiber based FML can be produced with all combinations with a moderate level of thermal residual stresses. In contrast, carbon fibers lead to very high thermal residual stresses. Therefore, it is worth considering glass fibers for applications where a lower stiffness is sufficient. Combinations of carbon fibers with aluminum layers exhibit very high thermal residual stresses causing mechanical problems besides the issue of electrochemical corrosion. Titanium alloys have the lowest CTE making them most suitable for combinations with carbon fibers.

The trends of thermal residual stresses depending on the material system used can be predicted accurate with both, FEA and analytical methods. However, FEA is the only way to determine stress peaks and stress distributions within the laminate. Otherwise, the application of analytical approaches has the advantage of fast and easy usage for the pre-design of material system. For the selection of promising material systems it is very efficient to evaluate and compare several material combinations by the analytical approach.

References