Multifunctional thermal barrier coating in aerospace sandwich panels

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1. Introduction

The concept of a multifunctional thermal barrier coating (TBC) in sandwich panels explored in the paper is concerned with two issues: delaying heat propagation to the interior behind the panel and enhancing structural response of the panel. These goals are pursued subject to a weight constraint. The multidiscipline problem that has to be addressed involves the solutions of the heat transfer and structural response problems, accounting for the effect of temperature on the properties of the materials constituting the sandwich panel. The latter effect makes the analytical solution of the heat transfer problem impossible (or impractical), although the structural problem may still be analyzed for a limited class of boundary conditions. Numerical solutions presented in the paper demonstrate the feasibility of the proposed concept.

Sandwich structures employed in aerospace applications are often exposed to thermal loading. The effects of such exposure include a degradation of the materials of facings and core, thermally induced stresses or instability, and reduced damage tolerance. Active and passive cooling, as well as functional grading, are among the methods of enhancement of the response of structures subject to thermal loads. In particular, functionally graded sandwich structures were considered both for an enhancement of their thermomechanical response as well as in such problems as low-velocity impact (e.g., Birman and Byrd, 2007; Kirugulige et al., 2005; Apetre et al., 2006). While most studies of functionally graded sandwich structures concentrate on grading of either the core or facing-to-core interface, the effects of in-plane grading of facings and variations in the thickness of facings in sandwich panels have also been considered (Birman et al., 2008; Nguyen et al., 2011a, 2011b).

Thermal barrier coatings have been extensively investigated (e.g., Evans et al., 2001; Abdul-Aziz et al., 2002; Cao et al., 2004). While their studies are often concerned with preventing debonding from the substrate, a possible contribution of the coating to mechanical response of the structure is seldom a major consideration. However, if the coating possesses high stiffness and strength, it may effectively enhance structural response, in addition to improving thermal characteristics. We explore such possibility in this paper adding very thin thermal barrier coating layers to a typical aerospace sandwich structure and monitoring their effect on through-the-thickness heat transfer as well as the thermomechanical stress distribution and stiffness (stability and fundamental frequencies). The main objective of the concept considered in this paper is to delay heating of the inner surface of the sandwich panel, possibly avoiding a need in active cooling and reducing temperature of the interior compartment under the panel. The second objective is improving the load-carrying capacity and thermomechanical response of the panel. We attempt to achieve both objectives without a significant increase in the weight of the panel.

Baseline panels considered in this study have metallic facings and core. In particular, metallic cores have been extensively
employed in aerospace applications as is evidenced from a number of previously published papers (Bart-Smith et al., 2002; Villanueva and Cantwell, 2004; Rakow and Waas, 2007). While the materials of facings and core are retained in modified panels, thin ceramic layers are added between facings and core to reduce heat transfer as well as increase the stiffness and reduce stresses throughout the panel.

2. Analysis

The problem analyzed in the paper is depicted in Fig. 1. A sandwich panel is subject to thermal load at one surface as a result of airflow. The baseline panel that is constructed of identical 0.102 cm thick titanium alloy (Ti–6Al–4V) facings and a titanium alloy (Ti–6Al–4V) 2.337 cm thick foam core is replaced with a modified counterpart that employs the same material of facings and core. In the modified panel the thickness of the core is reduced to 2.311 cm to allow for two symmetric 0.0127 cm thick TBC between each facing and the core (the effect of TBCs of different thicknesses was also considered in Fig. 6). The material of TBC is barium strontium aluminosilicate (BSAS) that has a low density (3.183 g/cm³), a broad range of operating temperatures allowing operations up to 1386 °C and a low thermal conductivity equal to 2.0 W/m·°C at room temperature (Patent US 7579085B2, August 25, 2009). Note that barium strontium aluminosilicate is a brittle material and it has a relatively low flexural strength of an order of 130 MPa, for a monolithic material, (Unal and Bansal, 2000). In case of a deposited coating, this strength may be smaller, possibly limiting the applicability of the considered design. While the increase in weight remains very small, TBCs both delay heat transfer to the colder surface and increase the strength and stiffness of the original design. The properties of facings, core and TBC employed in the following analysis were specified using data from Military Handbook (2001), Harris (2000), and Abdul-Aziz and Bhatt (2009) and Abdul-Aziz et al. (2002), respectively. A sample of the properties used in this study are shown in Table 1 ($E =$ modulus of elasticity, $\nu =$ Poisson’s ratio, $\alpha =$ coefficient of thermal expansion, $k =$ thermal conductivity).

2.1. Transient thermal problem

Thermal loading was determined for the flight at the supersonic speed (Mach number equal to 3.88) at the altitude of 21.34 km, at the ambient temperature of −55 °C (Fogiel, 1996). A turbulent airflow was assumed over the panel. Under these conditions, the adiabatic wall temperature ($T_{aw}$) of the panel surface exposed to the airflow was determined from (Ozisik, 1985):

$$T_{aw} = T_a + \frac{rV^2}{2C_P}$$

where $T_a$ is the ambient temperature, $C_P$ is specific heat of air, $V$ is the air speed, and the recovery factor $r = Pr^{1/3}$, $Pr$ being the Prandtl number.

The initial exposed surface temperature found under such conditions was 524 °C, but it slowly decreased with time as a result of the change in thermal conductivity of the exposed facing affected by temperature and the corresponding change in the Prandtl number. Temperature of the air outside the colder (inner) surface of the sandwich panel was sustained at 21 °C (room temperature). The dominant thermal boundary condition for the inner surface was convection.

The thermal flow was one-dimensional by assumption that the boundaries of the panel do not serve as heat sinks (a possible reference to heat-sink boundaries can be incorporated in the numerical solution, if necessary). However, even a one-dimensional heat transfer problem does not typically have an analytical solution, as long as one takes into account the effect of local temperature on material properties of the facings and core. Although, analytical models of material properties as functions of temperature have been suggested (e.g., Touloukian, 1967; Tanigawa et al., 1996), such models result in a differential equation of heat transfer with variable coefficients that has analytical solutions only in simplest superficial cases. For example, the properties of materials subject to an elevated temperature can be represented in a polynomial form (Touloukian, 1967):

$$P = P_0(T - T_0)^{−1} + P_1 T + P_2 T^2 + P_3 T^3$$

where $P$ is a property, $P_i$ ($i = −1, 0, 1, 2, 3$) are material constants and $T$ is temperature.

The one-dimensional dynamic heat conduction equation for an isotropic material is (Mills, 1995):

$$\frac{d}{dz} \left[ k(z) \frac{dT}{dz} \right] = \rho c \frac{dT}{dt}$$

where $z$ is a coordinate (in this case, this would be a coordinate in the thickness direction), $k(z,t)$ is a thermal conductivity, $\rho$ is density, and $c(z,t)$ is specific heat. If the conductivity and specific heat are functions of temperature resembling (2), the analytical solution of Eq. (3) becomes impractical. Accordingly, the following analysis was conducted numerically using Nastran-2004 and three-dimensional solid elements (the modeling scheme is shown in Fig. 2 that also lists nodal surface temperatures corresponding to the initial exposure time).

The general equation considered in transient analysis is (MSC Nastran, 2004)

$$[B] \left\{ \frac{du}{dt} \right\} + [K] \{u\} + [R]\{u + T_{ABS}\}^{4} = \{P\} + \{N\}$$

where $[B]$ = heat capacity matrix, $[K]$ = heat conduction matrix, $[R]$ = radiation matrix, $\{P\}$ = vector of applied heat flows that are either constant or functions of time, $\{N\}$ = vector of nonlinear heat flows that depend on temperature, $\{u\}$ = grid point temperature and $T_{ABS}$ = absolute temperature scale factor.

The MSC/NATRAN analyzer solves differential Eq. (4) with initial thermal condition specified in Fig. 2 using the one-step integration scheme. The time step employed in calculations was chosen $\Delta t = 0.01$ s.

An example of the through-the-thickness temperature distribution after a 3-h exposure to thermal loading is demonstrated in Fig. 3. As follows from this figure, the presence of TBCs changes both the thermal gradient through the thickness as well as the temperature on the exposed and inner surfaces of the panel. The temperature of the exposed surface is actually a little higher in the modified panel reflecting a low thermal conductivity of TBC layers. However, as a result of these layers, the temperature of the inner surface remains much lower in the modified panel, even after a 3-h exposure. A distribution of temperature through the thickness during the initial 30 min of flight is illustrated in Fig. 4 (baseline panel) and Fig. 5 (modified panel).

An interesting observation available from the comparison of Figs. 4 and 5 is that even though the conductivities of the panel materials depend on temperature, the temperature distribution through the thickness of each facing and core of the sandwich panel remains nearly linear. As the time of exposure elapses, the distribution of temperature through the thickness becomes more uniform, as anticipated. A sharp change in temperature between the facings and core observed in the modified panel is explained by the presence of very thin TBC layers that have a low conductivity.

The principal objective of the concept considered in the paper is to slow the process of heating of the inner surface of the panel. The effectiveness of the modified panel in addressing this objective is illustrated in Fig. 6. As follows from this figure, in both the baseline and modified panels the temperature of the inner surface
Fig. 1. Concept of sandwich panel with multifunctional TBC. The baseline sandwich panel is on the left and the modified panel with TBCs between the facings and core is on the right.

Table 1
Properties of materials of the sandwich panel.

<table>
<thead>
<tr>
<th>Property</th>
<th>Face sheet</th>
<th>Foam core (Ashby et al., 2000)</th>
<th>Thermal barrier coating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21.11 °C</td>
<td>537.78 °C</td>
<td></td>
</tr>
<tr>
<td>$E$ (GPa)</td>
<td>110.32</td>
<td>55.16</td>
<td></td>
</tr>
<tr>
<td>$v$</td>
<td>0.31</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ (1/C)</td>
<td>$8.73 \times 10^{-6}$</td>
<td>$1.01 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$k$ (W/m·°C)</td>
<td>7.30</td>
<td>13.30</td>
<td></td>
</tr>
<tr>
<td>Density (gm/cm$^3$)</td>
<td>4.43</td>
<td>4.43</td>
<td></td>
</tr>
</tbody>
</table>

Note: Properties of facing and core materials are shown for sample temperatures of 21.11 °C and 537.78 °C. For intermediate temperature values, the properties were generated using the methodology in Military Handbook (2001) and Harris (2000). The properties of TBC are shown for two sample temperatures. These properties were insensitive to temperature variations (Cao et al., 2004).

Fig. 2. The finite element model of the baseline panel is shown on the left. The modified panel is on the right: the only difference is the added thermal barrier coating layers between the facings and core.

Fig. 3. An example of temperature distribution after a 3-h exposure to thermal loading. The baseline panel is shown on the left; the modified panel is on the right. The numbers in color bars refer to °R (Rankine degrees). [For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.]
increases with time, but this increase slows with time of exposure and eventually, temperature approaches a steady state level. The steady state temperature of the inner surface is significantly smaller in the modified panel. Furthermore, even prior to the achievement of the steady state level, at any time instant, the temperature of the inner surface of the modified panel remains much lower than that in the baseline design. As an example, after a 0.78 h exposure, the temperature of the inner surface is equal to 481.11°C in the baseline panel and only 356.11°C in the modified panel (case 6 in Fig. 6). These observations reflect on the efficiency of TBC layers in sandwich panels where the task is slow the process of heating of the inner surface and reduce its steady state temperature.

A decrease of the temperature of the inner facing can significantly improve the response of the panel, even if this decrease is only of an order of 100°C. For example, the modulus of elasticity of the facing decreases by a factor of 1.5 if temperature is increased from 400°C to 500°C.

The results and conclusions regarding the efficiency of TBC in sandwich panels obtained in this section are not affected by the boundary conditions along the edges of the panel (except for the above-stated assumption that the edges do not serve as heat sinks) or by in-plane dimensions. However, the boundary conditions and dimensions affect the stress, stability and dynamics of the panel. Some of these issues are discussed below.

### 2.2 Static and dynamic response and merit of the modified panel

The evaluation of a thermomechanical response of a sandwich or laminated structure where temperature is nonuniform through the thickness introduces a peculiar element in the analysis if the effect of temperature on the material properties is accounted for. The structure that is typically designed symmetric with respect to the middle surface exhibits asymmetry due to a nonuniform...
degradation of properties. For example, in the present case, the stiffness of the exposed facing is smaller than that of the inner facing. The same asymmetric change in the stiffness is observed for the sections of core adjacent to the exposed and inner facets (the properties of the coatings are practically unaffected by temperature considered in examples). As a result, the structure that was designed symmetric about the middle surface acquires coupling stiffnesses, exhibiting bending-stretching coupling. Analytical solutions for shear-deformable sandwich structures with bending-stretching coupling are available for a limited number of boundary conditions. Besides the limitations introduced by boundary conditions, the temperature distribution through the thickness varies with time implying a need in a continuous update of the stiffness of the panel. Thus, the analysis is conducted numerically. For additional discussion on the effect of temperature-dependent properties on the response of structures, see Birman (2011).

The NASTRAN finite-element computer program (MSC Nastran, 2004) was used in the thermomechanical analysis of the sandwich panels. The sandwich panel (face sheets and core) was modeled by 3-D brick elements. The model consists of 255,000 nodes, 60,000 brick elements and 400 Rigid Body Element (RBE) joint locations. As follows from our analysis, increasing the number of elements does not result in a higher accuracy of either thermal or thermomechanical analyses. The panel was simply supported, so that while four edges could not move in the x-, y- or z-directions, their rotation was unconstrained. Such boundaries are encountered in cases where the edges are supported by stringers or frames of a low torsional stiffness but high bending stiffness that can be modeled as simple support. In-plane displacements along the edge are usually prevented by high axial stiffness of the supporting structure, while in-plane displacements in the direction perpendicular to the edge are absent due to the presence of adjacent panels possessing high in-plane stiffness. To simulate the boundary condition described above, RBEs were attached to the panel edges connecting the two face sheets as shown in Fig. 7. The midpoint of these RBEs was pin-jointed and prevented against the motion in the x- and y- direction for the edges x = constant and y = constant, respectively. In addition, vibrations of the panels were considered for the case where the edges were clamped (in-plane displacements of clamped panels were also prevented).

The length and width of the panel were equal to 63.5 cm, except for the buckling problem discussed below. The loading was represented by the thermal load described in the previous section and a uniform pressure equal to 317.16 kPa applied to the exposed facing of the panel. The chosen value of pressure is quite high being equal to 1/3 the yield stress of the titanium facing. Thus, we can monitor the response of the panel operating close to the failure load. The distribution of temperature being variable with time, thermal load and accordingly, the stresses in the panel were also time-dependent.

Deflections of the panels subject to thermomechanical loading are shown in Fig. 8. It is observed that the deflection is significantly reduced in the modified design as could be anticipated considering high stiffness of TBC and their location adjacent to the facing, i.e. at a large distance from the middle plane. A valid concern is related to the weight penalty associated with such improvement in the stiffness. This concern is addressed in Table 2 that presents a weight comparison between the baseline and modified panels with various thicknesses of TBCs. Notably, even if the thickness of TBC is increased to 0.0127 cm resulting in a very large enhancement of the stiffness (the examples considered in this paper consider only this thickness, except for Fig. 6), the weight increase compared to the baseline design is limited to 1.5%. The enhancement of the stiffness resulting in a significant reduction of deflections as shown in Fig. 8 also produces an increase of stability and the fundamental frequency of the panel. The resistance against such local failure modes as wrinkling and kinking would also be improved (the analysis of these modes is outside the scope of the paper).

Consider an increase in the fundamental frequency of the panel due to the introduction of TBC. Such increase is sometimes required in engineering applications where the goal is to “shift” the natural frequencies from the spectrum of possible driving frequencies avoiding resonance.

The frequencies vary with the time of exposure to thermal loading reflecting the process of heat transfer, changes in the thermal profile through the thickness and related changes in the material properties affected by local temperature. This is illustrated in Tables 3 and 4 (simply supported and clamped panels with identical in-plane boundary conditions, respectively). In both cases the increase in the fundamental frequency remained quite small reflecting the fact that natural frequencies are roughly proportional to a square root of the stiffness. The relative increase in the buckling load that is roughly proportional to the stiffness is much higher as shown below. The frequencies decrease with the time of exposure to thermal loading for both boundary conditions considered in Tables 3 and 4. This occurs as a result of the change of the thermal profile through the thickness of the panel as well as thermally induced compressive stress resultants (thermal couples that are also present have a minimal effect on the frequencies since sandwich panels considered in examples are predominantly geometrically linear systems). As the exposure time increases and the heat transfer approaches steady state, the frequencies stabilize. The mode shapes of both baseline and modified vibrating panels vibrating at their fundamental frequencies are identical as shown in Fig. 9. A similar pattern, i.e. insensitivity of the mode shape to the modification of the panel adding TBCs, was observed during the exposure to thermal loading for clamped boundary conditions. Based on the results shown here we have to conclude that if the goal of the modification is a higher fundamental frequency, adding TBCs appears to be ineffective.
In the present study, we also consider the stability problem for a square panel with the thickness-to-side ratio of 1/100 and the same through-the-thickness dimensions as previously discussed. The change in the in-plane dimensions compared to the previous case was due to the necessity to avoid local buckling of the facings (wrinkling occurred prior to global instability if the panels had smaller in-plane dimensions resulting in a higher overall stiffness and buckling load). The panel was clamped around the boundary and subject to uniaxial compression. The uniaxial buckling stress resultants evaluated at the room temperature were equal to $4.16 \times 10^6$ N/m for the baseline panel and $4.97 \times 10^6$ N/m for the modified panel. This presents a 19% improvement in the...
buckling load, further illustrating a possible multifunctional use of TBCs in sandwich panels. The mode shapes of buckling of the baseline and modified panels were nearly identical, as evidenced in Fig. 10.

Stress analysis represents significant interest for sandwich panels considered in relevant applications. As follows from the previous discussion, both the thermal profiles as well as thermally induced stresses vary with time. Moreover, the properties of the panel materials, including their stiffness, being temperature-dependent, mechanically induced stresses also change with time.

As an example, we illustrate the von Mises stresses in the exposed facing of the baseline and modified panels 10, 20 and 30 min after the exposure to thermal load (besides thermally induced contributions, the stresses in the panel are affected by uniform pressure of 317.62 kPa (46 psi) applied to the panel). The stresses in TBCs, the facing adjacent to the inner surface and in the core were also evaluated and found less dangerous than those in the exposed facing.

The stresses in the exposed facing shown in Figs. 11–13 increased with time of exposure approaching the yield stress of titanium (126 ksi). The reason is evident from the previous section.
where it was shown that temperature in the panel also gradually increases with time resulting in a degradation of the properties of the facing and core (TBC material was insensitive to temperature considered in examples). Notably, the stresses in the exposed facing of the baseline panel approach the yield limit after 30 min exposure (Fig. 13). However, the stresses in the modified panel remained much lower than the yield stress, even after such exposure.

The efficiency of the proposed concept in its aspect related the increased load-carrying capacity has to be considered against an increase in the weight of the panel. As has already been discussed in regards to Table 2, such increase remains small, even for panels with relatively thick TBCs. Here we define a measure of the efficiency, called a merit factor (M), as follows

\[
M = \frac{(\sigma/W)_{\text{base}}}{(\sigma/W)_{\text{mod}}} \quad (5)
\]

In (5), the ratios in the numerator and in the denominator represent the von Mises stress in the panel divided by the panel weight for the baseline and modified designs, respectively. The von Mises stress is determined in the element of the panel where such stress is the closest to the allowable or yield stress of the corresponding material. In the examples considered in the paper, the critical location was the center of the exposed facing. The merit factor defined by (5) reflects the improvement in the strength of the panel, subject to the constraint on its weight.

The merit factor of panels decreased with exposure time, being equal to 1.17, 1.11 and 1.08 after 10, 20 and 30 min exposure, respectively. Thus, the reduction in the stresses is particularly significant in the initial phase of thermal loading suggesting that the concept considered here may be particularly effective in case of a limited-time exposure.

3. Conclusions

The paper illustrates the concept of multifunctional thermal barrier coatings in sandwich panels. The multifunctionality is reflected in both the control of heat transfer through the panel as well as an improvement in the strength and stiffness. It is demonstrated that an improved performance can be achieved without a noteworthy weight penalty using currently available TBC materials. A major potential complication introducing the proposed design is related to manufacturing complications. The relevant manufacturing issues will be the proper bonding of the face sheet to the core. If the bond is weak, then delamination will occur. Also, there is a possibility of face sheet blow-up due to hot air from the core. Thus, the fabrication process has to be closely monitored.

The panel considered in the examples was subject to thermal loading for a representative high altitude supersonic flight. The heat transfer analysis was conducted by the finite element method since temperature-dependence of the conductivity results in a differential heat conduction equation with variable coefficients making an analytical solution impossible. It was shown that the temperature of the inner surface of the modified panel with TBCs remains significantly lower than that in the baseline panel throughout the entire time of exposure to thermal loading. After the initial transient period, the temperature of the inner surface stabilizes; the corresponding stable temperature of the modified panel is much lower than its counterpart in the baseline panel. This represents an important improvement in applications where it is necessary to shield the interior from elevated temperatures.

Besides the improvement in thermal behavior, the strength and stiffness of the representative panel were noticeably increased as a result of the introduction of TBC layers. The improvement in the strength constituted by reduced stresses was particularly noticeable in the initial transient period of the exposure to thermal loading. A higher stiffness of the modified panel resulted in a small increase of the fundamental frequency and a larger enhancement of stability. The improvements in both the thermal performance as well as in the strength and stiffness were achieved at the cost of a minimal increase in weight. Accordingly, it is concluded that currently available materials make the application of multifunctional TBCs in sandwich panels both feasible and attractive.

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References


