Thermal Behaviour of a Thin Sandwich Composite Structure With Nonwoven Polyester Mat Core

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Abstract: - The paper presents the thermal behaviour of a sandwich structure with thin nonwoven polyester mat as core. The structure presents dissimilar skins from which one is a glass fabric reinforced polyester. Some simulations regarding the thermal conductivity of thermo-electric conductive resins reinforced with various carbon fibres and presenting different fibres volume fractions have been also presented. This simulation has been carried out using a computer software developed by Clyne and Withers from the Department of Materials Science within the Cambridge University, United Kingdom. Thermal expansions have been measured using a DIL 420 PC dilatometer from NETZSCH, on both glass fabric reinforced polyester skin and for the whole structure. The coefficients of thermal expansion have been determined only for the structure’s upper skin. For each sample, two successive heating stages in order to size the influence of the thermal cycling, and temperature interval from 20°C to 250°C, at a heating rate of 1 K/min have been used. To eliminate the system errors, the dilatometer has been calibrated by measuring a standard SiO₂ specimen under identical conditions.

Key-Words: - Thermal expansion, Thermal conductivity, Core, Sandwich, Nonwoven polyester mat, Coefficient of thermal expansion.

1 Introduction
In general, a sandwich structure is manufactured of three layers: two cover layers called “skins”, that form the carrying structure, layers composed of stiff and resistant material, and an intermediate layer named “core”, which has the main purpose to sustain the skins and to give stiffness to whole structure [1]–[6]. This stiffness is obtained actually through thickening the composite structure with a low-density core material. This leads to a substantial increase of flexural rigidity of the structure, on the whole, without a significant increasing in its entire weight [7]–[13].

The quantitative anisotropy of the carbonic materials can be evaluated through texture and determined by X-rays diffraction techniques. So, the texture of carbonic materials may vary in a wide range, depending on the precursor and thermal and thermo-mechanic treatment [14]. In general, conductive polymer matrix composites (PMCs) can be manufactured by embedding highly conductive materials like metals, carbon fibres and particles in the matrix. Unidirectional tapes of carbon fibres represent a better solution to increase thermal conductivity of PMCs than conductive particles since these particles have to be embedded in a continuous way to form a network in the matrix. Thermal conductive particles-reinforced composites present significant technologically problems. For instance, for a great importance is the consistency and the continuity of the particles network [15]. So, embedding conductive fibres in matrices represent a better choice [16]-[21].

Using the percolation theory, this thermal conductivity of particles-reinforced composites can be described and understood. See for instance the reference [22]. This theory represents the simplest way but not an exactly model to display this thermal conductivity.

Sandwich structures are more and more used in various applications due to their high stiffness at bending and seen as a multibody system [23]. Nowadays, there are a great variety of cores such as rigid foams, hexagonal structures made from...
thermoplastics, metallic and non-metallic materials, expandable and fireproof materials, balsa wood, etc.

2 Problem Formulation

In general, composite laminates are formed by thin layers called laminae. These laminates present a quite low stiffness and flexural rigidity. A solution could be their stiffening using ribs. However, there are constructive situations when these ribs can not be used. Another solution could be the increase of layers number that composes the structure but this leads to the disadvantage of the increase of resin and reinforcement consumption with economic and environmental consequences. A better and common solution is to use a thin nonwoven polyester mat as core. Carbonic materials present a significant anisotropy of the physical properties due to the layered structure of the graphite. From this reason, the graphite crystal properties are very different along its axial and transverse direction. So, simulations regarding the thermal conductivity of polymer matrix composites with carbon fibres as reinforcement, both in axial and transverse direction can give further information of this anisotropy.

3 Thermal Conductivity Simulation

Let us consider a unidirectional fibre formed of infinite sites equal spaced. Each site has the probability \( p \) to be occupied and accordingly, \( 1 - p \) sites to be empty. Fig. 1 shows an example of percolation in a unidirectional fibre, seen as a 1D lattice. The empty circles represent the empty sites and the solid circles are occupied sites. A cluster represents a group of nearest occupied sites. The number of clusters \( n_s(p) \) denotes the clusters of size \( s \). In the example presented in fig. 1 there are one cluster of 4 sites, one cluster of 3 sites, one cluster of 2 sites and one cluster of one occupied site. The aim is to know the occupation probability to obtain for the first time an infinite cluster. This infinite cluster represents physically the thermal conductivity in a unidirectional conductive fibre. Through an infinite length of a fibre, a percolation cluster can be achieved if all sites are occupied, this means that a percolation threshold \( p_t \) of value 1 must be reached. If the occupation probability \( p \) is small, there is a very small chance to have a cluster percolating two opposite borders (for instance, from left to right in a 1D lattice) [22].

Let us denote \( P(p, L) \) the probability that a lattice of unidirectional size \( L \) percolates at occupation probability (concentration) \( p \).

![Fig. 1. Simulation of percolation in a unidirectional fibre](image)

When, \( L \to \infty \), Stauffer and Aharony ignored the border sites of the lattice and described the probability of an arbitrary left hand side \( s \)-cluster, as [22]:

\[
\lim_{L \to \infty} P(p, L) = \begin{cases} 0 & \text{for } p < p_t, \\ 1 & \text{for } p \geq p_t, \end{cases}
\]

(1)

with the assumption that the occupancy of each site is independent of the state of any other site.

Other cluster number distributions \( n_s(p) \) expressed by Stauffer and Aharony, are [22]:

\[
n_s(p) = (1 - p)^s \exp\left(\ln(p^s)\right), \quad (3)
\]

\[
n_s(p) = (1 - p)^s \exp\left(s \ln(p)\right), \quad (4)
\]

\[
n_s(p) = (p_t - p)^s \exp\left(-\frac{s}{s_t}\right), \quad (5)
\]

with a definition of a characteristic cluster size [22]:

\[
s_t = \frac{1}{\ln(p)} = \frac{1}{\ln(p_t - (p_t - p))} \to \frac{1}{p_t - p} = \frac{1}{p_t - p}^{-1} \quad \text{for } p \to p_t, \quad (6)
\]

where \( p_t = 1 \) have been used.

4 The Sandwich Structure

To increase the stiffness of common fibre-reinforced composite laminates, and to avoid the previously presented disadvantages, the following structure is presented:

- 1 layer RT500 glass roving fabric;
- 2 layers RT800 glass roving fabric;
- 1 layer CSM450 chopped strand mat;
- 1 layer nonwoven polyester mat as core;
• 1 layer CSM450 chopped strand mat;
• A usually used gelcoat layer.

It can be noticed that this structure presents dissimilar skins. The core presents the most important influence in the overall structure’s stiffness and flexural rigidity. The core material is a random oriented noncontinuous nonwoven polyester mat containing microspheres that prevent excessive resin consumption. The most important features of the whole structure using this kind of core are:
• Stiffness increase;
• Weight saving;
• Resin and reinforcement saving;
• Fast build of the structure’s thickness;
• Superior surface finish.

The nonwoven polyester mat is soft, present excellent resin impregnation and high drapeability when it is wet and therefore is suitable for complex shapes. It is most often applied against the gelcoat to create a superior surface finish for instance on hull sides. The applying of the nonwoven polyester mat against the gelcoat layer is more important when dark gelcoats are used, to prevent the appearance of the glass fibres reinforcement. This material presents a good compatibility with the polyester, vinylester and epoxy resins and is suitable for hand lay-up and spray-up processes. Other processes like vacuum bag moulding can be used also.

Regarding the thermal approach of this structure, the expansions of the upper skin as well as for the whole sandwich structure have been measured. Coefficients of thermal expansion and the alpha feature for the upper skin have been also determined. The coefficients of thermal expansion have been measured using a DIL 420 PC dilatometer from NETZSCH (Germany), on both glass fabric reinforced polyester skin and the whole structure. For each sample, two successive heating stages in order to size the influence of the thermal cycling, and temperature interval from 20°C to 250°C, at a heating rate of 1 K/min into a static air atmosphere have been used. To eliminate the systems errors, the dilatometer has been calibrated by measuring a standard SiO₂ specimen under identical conditions.

5 Composites Used In Simulations

The simulation of thermal conductivity has been carried out on following composites with electrical applications:
• Matrix: Polyurethane resin type RE-12551; Fibres: carbon type T300/PAN 1373K;
• Matrix: Polyurethane resin type RE-12551; Fibres: carbon type T300/PAN 2673K;
• Matrix: Pitch-matrix 1373K; Fibres: T300/PAN 1373K;
• Matrix: Pitch-matrix 1373K; Fibres: T300/PAN 2673K;
• Matrix: Pitch-matrix 1373K; Fibres: P55/PITCH 1373K;
• Matrix: Pitch-matrix 1373K; Fibres: P55/PITCH 2673K;
• Matrix: Pitch-matrix 2673K; Fibres: T300/PAN 1373K;
• Matrix: Pitch-matrix 2673K; Fibres: T300/PAN 2673K;
• Matrix: Pitch-matrix 2673K; Fibres: P55/PITCH 1373K;
• Matrix: Pitch-matrix 2673K; Fibres: P55/PITCH 2673K.

This simulation has been carried out using a software developed by Clyne and Withers from the Department of Materials Science within the Cambridge University, United Kingdom [24].

6 Results

Following input data have been used:
• Fibres volume fraction: 50%;
• Fibres aspect ratio: 10×10⁻²;
• Thermal conductivity of the unreinforced matrix type RE-12551: 0.73 W m⁻¹ K⁻¹;
• Thermal conductivity of the unreinforced Pitch-matrix type 1373K: 6.2 W m⁻¹ K⁻¹;
• Thermal conductivity of the unreinforced Pitch-matrix type 2673K: 257 W m⁻¹ K⁻¹;
• Thermal conductivity of the reinforcement type T300/PAN 1373K: 8.5 W m⁻¹ K⁻¹;
• Thermal conductivity of the reinforcement type T300/PAN 2673K: 76 W m⁻¹ K⁻¹;
• Thermal conductivity of the reinforcement type P55/PITCH 1373K: 113 W m⁻¹ K⁻¹;
• Thermal conductivity of the reinforcement type P55/PITCH 2673K: 196 W m⁻¹ K⁻¹.

The thermal conductivity has been determined both in axial and transverse direction of the composite. The results are presented in figs. 2 – 7. Curves of thermal expansion determined experimentally for two heating processes in case of the studied sandwich structure as well as for the upper skin are presented in figs. 8 and 9. In fig. 8, the negative thermal expansion in the first heating process is due to the beginning of curing in the
upper skin structure. Regarding fig. 9, in the second heating stage, the significant peak is due to the high shrinkage that took place in the sandwich structure.

In fig. 10, following thermal features have been determined on the structure’s upper skin in the first heating process:
- The thermal expansion (continuous line);
- The coefficient of thermal expansion (also known as technical alpha – dashed line);
- The alpha feature (dotted line).

![Fig. 2. Thermal conductivities on axial direction of various carbon fibres-reinforced polyurethane resin](image)

![Fig. 3. Thermal conductivities on axial direction of various carbon fibres-reinforced PM1373K resin](image)

![Fig. 4. Thermal conductivities on axial direction of various carbon fibres-reinforced Pitch-matrix type PM2673K resin](image)

![Fig. 5. Thermal conductivities on transverse direction of various carbon fibres-reinforced polyurethane resin](image)
Fig. 6. Thermal conductivities on transverse direction of various carbon fibres-reinforced Pitch-matrix type PM1373K resin

Fig. 7. Thermal conductivities on transverse direction of various carbon fibres-reinforced Pitch-matrix type PM2673K resin

Fig. 8. Upper skin thermal expansions determined in two heating processes

Fig. 9. Sandwich structure’s thermal expansions determined in two heating processes

Fig. 10. Structure’s upper skin thermal expansion, alpha feature and coefficient of thermal expansion determined in first heating process
7 Conclusions
While the thermal conductivities on axial direction of composites based on PU and PM1373K resins are very similar and present an increased distribution, the PM2673K based ones exhibit scattered values and have a decreased distribution. While the thermal conductivities on transverse direction of composites based on PU and PM1373K resins present an increased distribution and exhibit scattered values, the PM2673K based ones present very close values.

References: