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Monitoring of the curing process of composite structures by tunnelling junction sensors

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ABSTRACT

In this work, tunnelling junction sensors (TJS) are proposed for monitoring the curing of Carbon Fibre Reinforced Plastic (CFRP). Tunnelling junction sensors are very sensitive to temperature changes; therefore they are suitable for this application. TJS are manufactured by Low-Pressure Chemical Vapour Deposition (LPCVD) and electronically characterized to obtain their $V(I)$ diagram. One sensor is embedded on a carbon–epoxy plate for measuring temperature evolution during composite's autoclave cycle. By means of a temperature–voltage–time curve, the evolution of sensor's signal related to temperature changes can be tracked. The main goals are to verify the viability to apply this technology to composite's curing process and to provide a first approach of the initial state of the composite plate by verifying the temperatures at each curing stage. Both purposes were achieved and help to better understand the composite polymerization process, which has a strong influence on the composite's mechanical performance.

1. Introduction

The quality control of long-fibre epoxy–carbon composite structures represents a technical and economical challenge for many industries such as aeronautics, aerospace and fluids transport. Because these structures are made up by superposing numerous layers with different fibre orientations, one upon each other; they allow placing measurement devices, such as thermocouples or strain gauges between their layers. This monitoring technique provides survey of composite's properties throughout the manufacturing process and it also can give indications of the mechanical and thermal behaviour during service conditions. This practice is known as in-core instrumentation, and many studies have underlined its value added to survey the through-the-thickness properties of composite materials [1–4]. However, composites in-core instrumentation still exhibits difficulties which retard its fulltime application in the industry. Sensor's size, autonomy and wire connections are the major issues to deal with.

Several researchers have shown their interest on the thermal phenomena which occur during composites curing [5–7]. The autoclave process is widely used to manufacture high performance composite structures in aeronautics. The quality of the composite parts is obtained thanks to the association of three curing parameters which are temperature, pressure and vacuum. Each one of them has an important influence on the initial properties of the material, such as fibre volume ratio, resin volume ratio and porosity density. These initial properties will also have a major impact on the final mechanical properties of the composite.

In the case of thermoset composite systems, the matrix reticulated network structure (MRN) is built during polymerization when heating activates chemical reactions responsible of curing and solidification of the matrix. The MRN provides cross-links that bond one polymer chain to another, making the material more rigid under loading. The expansion phenomena which accompany

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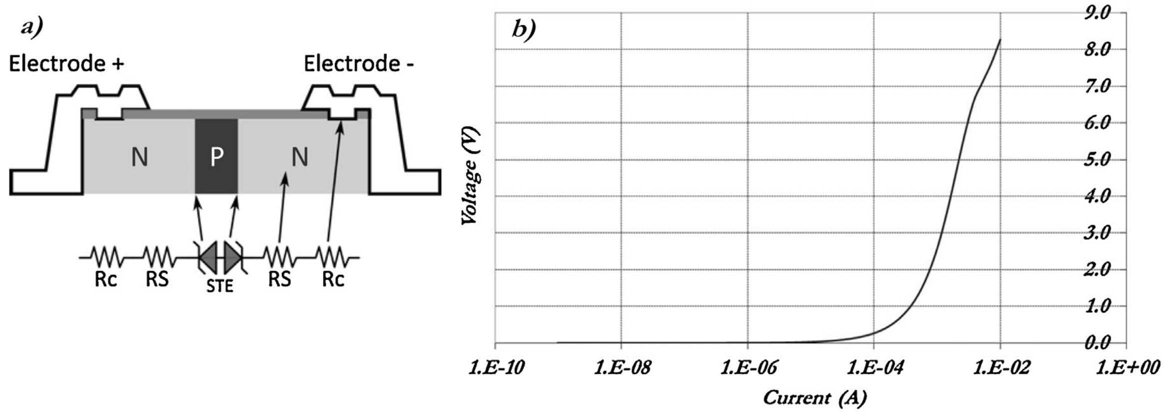

Fig. 1. The tunnelling junction sensor with a) general side-view schematic and b) $V(I)$ voltage–current characterization.

the curing impose compressive stresses on reinforcement fibres and produce internal stresses in the composite material. Therefore, the heating rate and the curing temperature are two of the main parameters to survey inside the autoclave [8,9]. Thermocouples are widely used to track the temperature inside the autoclave chamber and they are also employed to know the surface temperature of the composite structure. However, these devices are not quite adapted to measure the in-core temperature of the composite, because its larger thickness (at least 500 μm) compared to the composite's plies (about 250 μm). In addition, the difference between the coefficient of thermal expansion (CTE) of the metallic wire of the thermocouple and the carbon fibres of the composite could cause additional residual stresses which make them not suitable for this task.

With the aim of improving these drawbacks of composite instrumentation, research has been conducted to develop multi-parameters devices, which could detect many autoclave variables, including temperature. One type of these new devices, which shows strong potential to monitor thermal phenomena, is the "tunnelling junction sensor (TJS)" [10–12] which takes advantage of the tunnelling effect and its dependency on temperature. By polarizing the TJS with an electrical current, this device returns a voltage that depends on the temperature of the surrounding environment. Furthermore, the TJS dimensions, typically less than 300 μm of thickness, make them better suited to embed inside composite materials with a minimum layout alteration.

In this paper, the goal is to have a deeper comprehension of the capabilities of the TJS to identify temperature variations inside composite structures. First, a general explanation of the TJS functioning principle is provided. Then, the TJS manufacturing procedure is described. After that, the embedding procedure of a TJS inside a composite plate is cited; with the aim of testing the TJS in a composite's natural curing conditions. Finally, the TJS sensitivity to thermal changes is obtained, proving them comparable to common thermocouples in composite monitoring applications.

2. Tunnelling junction sensors (TJS)

Tunnelling junction sensors (TJS) are electronic devices which take advantage of inverse polarization of Zener P–N junctions. During the last decade, the LAAS has tested the TJS on micro-fluids applications and as thermal micro-actuators [10,11]. These sensors have been developed in order to measure different variables such as temperature, strain and pressure with the aim to create a multi-physics device. The TJS consist of a silicon polycrystalline prism doped with phosphorus and boron by Low-Pressure Chemical Vapour Deposition (LPCVD) to form P^+/N^- junctions. The P^+/N^- junction, known as Symmetric Threshold Element (STE), can be electrically considered to be two Zener diodes connected at the cathodes. The positive electrode is inversely polarized and the negative electrode is directly polarized (Fig. 1a). With this

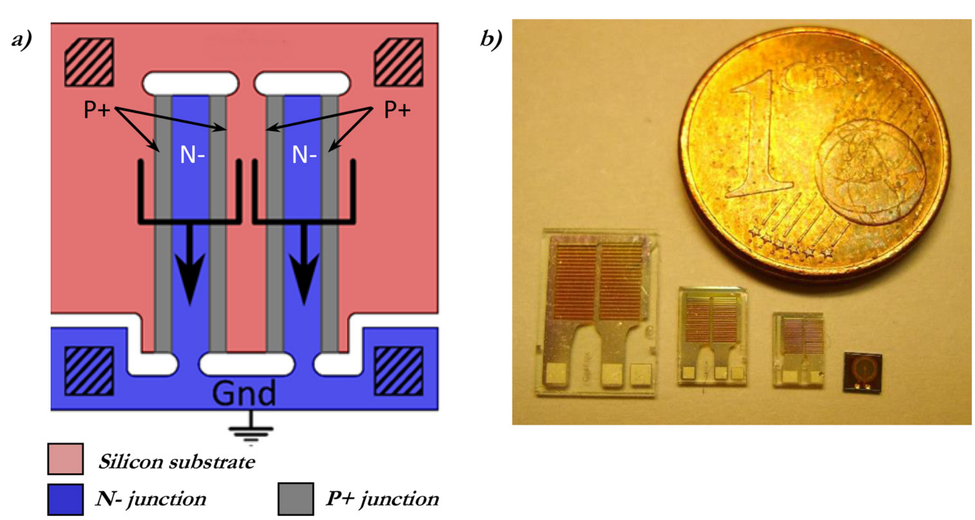

Fig. 2. Design of the tunnelling junction sensor (TJS) with a) top-view schematic and b) four finished TJS of different sizes created by the LAAS.