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A review of manufacturing techniques of smart composite structures with embedded bulk piezoelectric transducers

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Since the mid-1980's, sensors and actuators have been combined with composite materials in order to enhance and increase the functionalities of the resulting products. These innovative devices are called intelligent, adaptive or smart structures. Their main applications are related but not limited to vibration control, structural health monitoring, shape control and energy harvesting. One possible way of developing these devices is to embed the smart materials inside the structure. In this case, the main challenge is the way of embedding the smart material during the manufacturing process. This review presents the key elements of the manufacturing process, provides an overview of the techniques developed to embed the bulk piezoelectric transducers in the composite and details the achievements made with them. In conclusion, some guidelines for futures researches and developments are proposed.

Keywords: composite materials, smart structure, piezoelectric transducer, manufacturing techniques, embedding

1. Introduction

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone [1]. Currently, composite materials refer to materials containing strong fibres embedded in a weaker material called matrix [2]. The resulting material is capable of intermediate mechanical performance between those of the matrix and those of the fibres but with other specific properties [3].

The advantages of composite materials with respect to bulk materials are mainly high strength and stiffness, low mass density, good fatigue resistance, excellent fire resistance as well as the ability to tailor the material for optimum performance. Moreover, composite materials do not corrode and are not sensitive to common chemicals used mostly in engines [1–4].

The shortcoming of composite materials can be divided in three categories [1–4]:

- weakness to delamination or ply separations; low-velocity impact resistance; inability to yield; low damping ratio; impact of temperature and moisture on their mechanical

performance (particularly, when aging under the action of moisture and heat);
- difficulty in refurbishing them; toxicity of the smokes from their combustion; and the difficulty to mechanically connect them to their environment;
- high raw material costs and high fabrication and assembly costs.

Category 1 is dealt with by tailoring the materials to adjust to the corresponding structures. Tailoring means adapting the materials to interact with their environment in order to reflect the functionalities of the new devices. This is usually achieved during the method of production. Category 2 and Category 3 are, on the other hand, achieved by developing new base materials.

Composite structures including smart materials are also known as intelligent structures [5], adaptive structures [6] or smart structures [7]. In this paper, the term 'smart' is used. Before describing Smart Composite Structure (SCS), a smart structure is defined.

In 1996, Spillman, Sirkis and Gardiner [8] provided a definition after running a large survey. A smart material/structure is a physical material/structure having:

- A definite purpose,
- Means and imperative to achieve that purpose,
- A pattern of functioning similar to a biological entity

Smart materials or structures are materials or structures that change properties according to stimuli: under a certain input, they produce a predictable and repeatable response, or output [9].

On the other hand, the basic components of any smart system have been summarized by Akhras [10] as: (*their equivalents in the human body appearing in parentheses*)

- Data acquisition (tactile sensing): collect the required raw data needed for an appropriate control and monitoring of the structure.
- Data transmission (sensing nerves): forward the raw data to the local and central control units.
- Command and control center (brain): analyze the data, reach the appropriate conclusion and determine the specific actions.
- Data instructions (motion nerves): transmit the decisions and the associated instructions back to the members, and
- Controlling devices (muscles): take action by triggering the controlling devices/units.

Stacks of physical couplings can be used to obtain smart materials or by extension, smart structures. One possible way to sort the smart materials/structures is to classify them by input and output. Figure 1 represents their main functionality as well as their selection criteria [9, 11]. For example, photochromic materials are represented by the link between the input 'light' and the output 'colour'. Additionally, some of these materials exhibit a bi-directional response/behavior. On one hand, they react to an input by creating a specific output, and, on the other hand, they react to the former output by having an effect on the input. For example, piezoelectric materials respond to an electric charge or a variation in voltage by generating a mechanical deformation, and vice versa. These events are called direct and converse effects.

Conversely, a smart composite structure is a structure with embed smart materials. Consequently, the main factor is the way of embedding the smart material during the manufacturing process.

The present review is focused on the manufacturing techniques developed to embed bulk piezoelectric transducers in the composite material. As expected, PZT, or lead zirconate titanate, are the most widely piezoelectric ceramic material used as transducers [5, 7, 12–50]. Only laminates and not sandwich-structured composites [6, 51, 52] are considered in this state-of-the-art review.

2. Specifications and technical requirements for a smart composite structure

A fully distributed set of transducers is usually embedded in the smart composite structure during the manufacturing process. To guarantee the transducers' efficiency and to preserve the geometrical and material properties of the host structure, several major technical issues were identified as having a strong impact on the manufacturing process [44, 53], including the need to:

- Electrically connect a large number of transducers in order to act on the whole structure. This requirement uses the distributed network to modify the structural behaviour of the system over a wide range of excitation frequency or more generally over a wide range of multi-physical excitation;
- Make each transducer electrically independent. This is particularly important when developing carbon fibre-reinforced composite structures which are naturally conductive. The use of semi-finished products can provide a good electric insulation solution;
- Perfectly couple exogenous element with the composite material as to guarantee the transducers' efficiency and reduce the risks of delamination or other failures;
- Accurately master the location of the transducers into the structure in order to create symmetric arrays of transducers and thus a highly symmetric distributed network. This approach can provide the advantage of controlling the guided waves propagating into a thin structure;
- Limit the 'cross-talk' between the different embedded elements. A technical requirement has to be defined in order to set a design rule concerning the minimum pitch between two electrical conductors or a minimal distance between two transducers;
- Limit the thickness variation due to the piezoelectric inclusions. These inclusions may inevitably modify the thickness of the structure. In addition, the electrical connection base on conventional welding is not advisable due to the resulting excess thickness and the potential

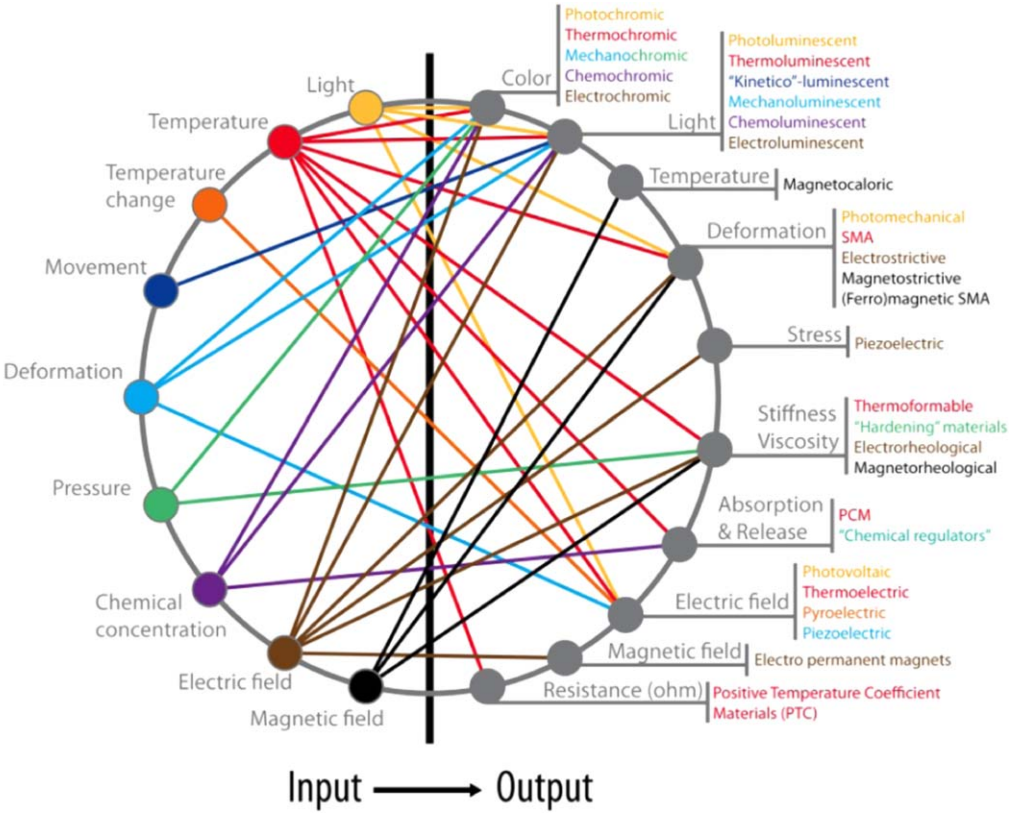

Figure 1. One possible classification of smart materials (reproduced with permission from[9]).

Table 1. Classification of the main manufacturing processes of composite structures [2, 54, 55].

Manufacturing process	Pressure (bar)	Temperature (°C)	Characteristic
Contact Molding/Spray-up molding	Manual	Ambient	Large structures, Slow, Laborious
Compression molding	50–100	Ambient or 120–150	
Vacuum molding	Vacuum	Ambient, up to 100	Slow, Laborious, reliable
Autoclave molding	7	180	Slow, Laborious, reliable, expensive
Resin Injection molding	up to 5	50–60	Fast, High volume, thermoplastics
Filament winding	No pressure	Ambient or higher	Moderate, speed, complex geometry, Hollow parts
Sheet forming	15–90	120–280	Fast, flexible
Pultrusion			Continuous, constant cross-section parts
Forming by stamping	150–200	200	
Resin Transfert Molding	Vacuum or 1–7	80	Fast, complex parts, good control of fiber orientation

creation of a wedge. Such a wedge could break the piezoceramics during the manufacturing process, thus ruining the transducer;

- Build specific shaped structures (for instance, bi-concave structures) to adapt to a wide range of real applications;
- Construct a robust link with the outside structure to provide energy or modify the control or the behavioral law in real time;
- Include the recycling and/or the final disposal aspects in the manufacturing process (i.e. bio-sourced materials);

All the manufacturing techniques used to produce smart composite structures had been established in order to follow all or part of these specifications and technical requirements.

3. Manufacturing processes of smart composite materials

Table 1 presents many manufacturing processes of composite structures. However, the main steps are always the same and can provide a classification with respect to their main characteristics [54] such as:

- Types of matrix (thermoplastic or thermosetting resins) and reinforcement (continuous fibres, mat, fabrics …) with an accurate fibre placement (proper orientation of the fibres);
- Mastering the shape and appropriate dimensional control of the final part;

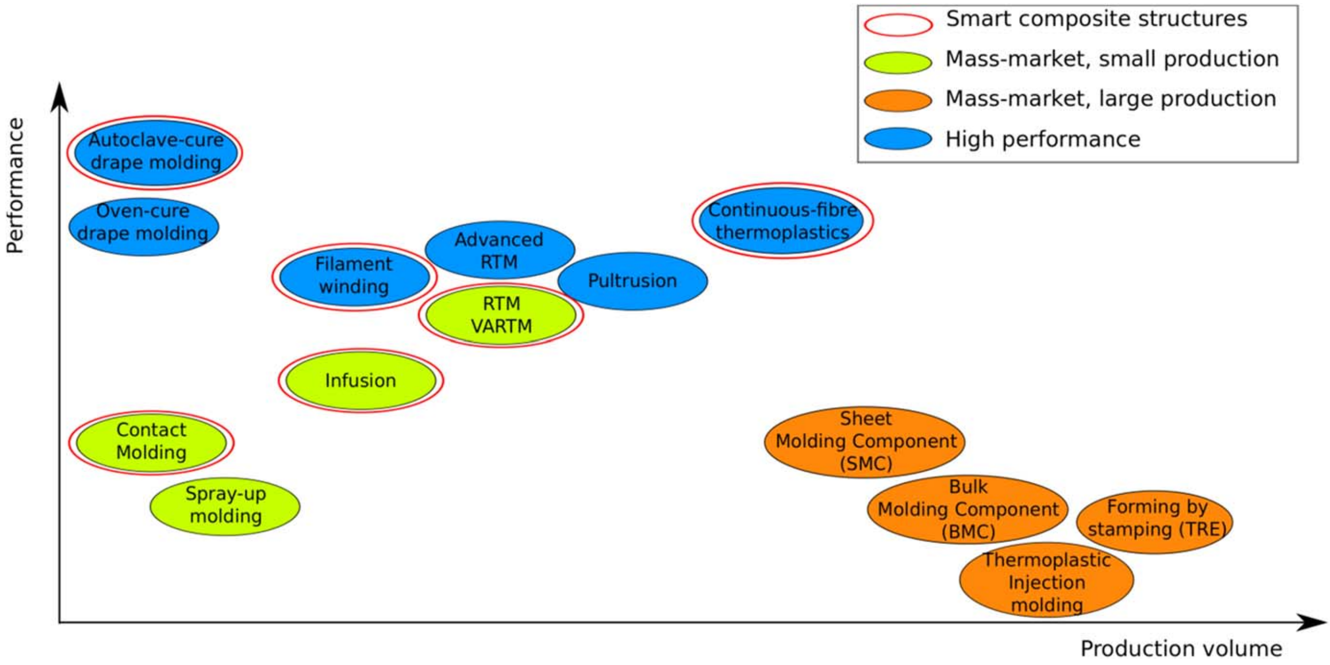

Figure 2. Main manufacturing processes versus performance and production volume.

Table 2. Manufacturing processes used for smart composite structures.

Manufacturing process	References
Contact molding	[36]
Autoclave	[5, 7, 12–23, 25, 27, 29, 31, 33, 35, 42, 43, 45, 50]
Vacuum assisted process (VARTM)	[32, 34, 40, 44, 49]
RTM	[26, 34, 40]
Infusion	[37–39, 41, 46–48]
Filament-winding	[24, 30]
Combination of filament-winding and autoclave	[28]

- Polymerization (room temperature or low-medium-high temperature). This step is essential in order to obtain a proper curing or correct solidification of the resin.
- Compaction (low or high pressure, vacuum or ambient). This element is related to the fibre volume fraction. The idea here is to have a limited amount of voids and defects and guarantee a good bonding between the matrix and the fibres.
- Inclusion of the piezoelectric transducers in order to tailor the composite structure for different applications.

  All these points impact directly the functionality and mechanical properties of the final product. Consequently, the choice of factors for a manufacturing process is:
- The technical requirements for the mechanical part (mechanical, chemical, thermal or electrical strength, surface aspect, shape, dimensions…);
- The type of material (quality and surface aspect);
- The production volume;
- The part complexity (type of production, part performance);
- The capital for investment.

Figure 2 provides a subjective overview of the main manufacturing processes of composite structures as function of the performance of the product and the expected volume production [56, 57]. Table 2 provides the processes used to manufacture these smart composite structures as identified in figure 2.

4. Manufacturing techniques of smart composite materials

4.1. Structure type

Two major mechanical parts of a smart composite structure are widely investigated: the beams [5, 13–15, 18, 20–23, 32, 35, 37–39, 41, 46, 47, 49, 50] and the plates [7, 12, 16, 17, 19, 22, 26, 27, 29, 31, 33, 34, 36, 42, 43, 45, 48]. This approach is mainly due to the ease of modeling these two parts. Moreover, many structures or parts of, such as bridges, airplane wings, hoods, etc.., can be represented by these structural elements.

However, in order to analyze the feasibility and functionality of complex composite structures, it is also necessary to master their manufacturing process as well as test them physically and not only numerically. Few authors have dealt with these complex smart composite structures. Lin *et al* and

Figure 3. Picture of the piezoelectric patch embedded in the blade during the lamination process (reproduced with permission from[40]).

Qing *et al* have presented the functionality of a fuel bottle [24, 30] for structural health monitoring. A simplified version of the Hypseo satellite momentum wheel support frame have been analyzed by Sala *et al* in order to implement an active vibration stabilization strategy [25]. Pfeiffer *et al* have implemented a compensation strategy of focal plane distortions of a simplified tripod for a space telescope [28]. In the Bachmann and Delpero PhD theses, different piezoelectric shunt damping strategies have been applied to rotating blades presented in figure 3 [34, 40]. A cantilever beam with an I-shaped cross-section thin wall and hollow profile has been investigated by Salloum to also test a vibration attenuation approach with shunted piezoceramics [45]. As depicted in figure 4, Meyer *et al* have developed an automotive spoiler with 50 embedded piezotransducers in order to damp the guided waves propagating in the structure [44].

4.2. Fibres/matrix type

The choice of the couple fibres/matrix is highly important to meet the different technical requirements such as the mechanical strength, the temperature stability, the surface aspect etc. Furthermore, nanofillers can be added to the matrix to change its properties [58]. A vast majority of available papers have described the use of a thermosetting resin with different types of fibres:

- Carbon Fibre Reinforced Polymer (CFRP). This usually means carbon fibres with an epoxy resin (or Graphite fibres and an epoxy resin) [5, 13–25, 28–31, 33, 34, 40, 42, 45];
- Glass Fibre Reinforced Polymer (GFRP);
- Glass fibres and an epoxy resin [5, 7, 12, 14, 18, 27, 32, 35–39, 41, 42, 45–47, 50];
- Glass fibres with a polyester resin [26, 44, 48, 49].

Several approaches can explain this hegemony of the thermosetting resin. Once the curing process is done, irreversible chemical bonds are formed. This provides an excellent structural resistance and a high heat resistance for quite cost-effective processes. However, the manufactured composites cannot be recycled and repaired.

These drawbacks have led some researchers to investigate the use of thermoplastics. The advantages of these materials are high recyclability, repair capabilities (possible remolding and reshaping) and high impact resistance. But, unfortunately, these processes are quite expensive comparatively to those with thermosetting resins. Moreover, these composites can melt with a temperature increase. Bronowicki *et al* have studied two different variations [13]: Graphite fibres with a polyarylsulfone resin and Graphite fibres with a PolyEtherEtherKetone (PEEK) resin. In this latter prototype, the PZTs have been partially dipoled and cracked. Consequently, the smart structure became non-functional. Another structure made of glass fibres and PEEK has been fabricated by Fairless *et al* and was fully functional [12].

4.3. Reinforcement forms

The concern over the reinforcement forms is on how the fibres can be joined together. The arrangements of the fibres have a major influence on the final mechanical properties of the manufactured product [59].

As presented by Hoa [54], the fibres used appear at different scales and under many different forms. Figure 5 shows different scales of the fibre forms. At a smaller scale (level a) are the individual filaments (or fibres) with diameters of about 10 microns. Tows (or strands) consisting of thousands of individual untwisted filaments (level b) can be combined either with or without the addition of resin for adhesiveness. Yarns are the twisted tows. If resin is used, the tows can be combined to form tapes [24, 28, 30]. The tows can also be woven together to make woven fabrics [12, 14, 18, 25, 27, 29, 34, 36, 43, 50], or the tows can be braided or knitted together to make fibre preforms (level c). Mat is a sheet-like material consisting of randomly oriented chopped fibres which are held together by a binder [26, 44, 48, 49]. A unidirectional fabric is one in which the majority of fibres run in one direction only [5, 7, 13, 15–17, 19–23, 28, 31–33, 35, 37–41, 45–47]. The fibres along the other directions hold the fibres in position.

4.4. Dimensional control

The structure shape and dimensions as well as the surface aspect are directly related to the selection of the manufacturing process. As shown in table 2, most authors have selected a process leaving one surface raw [7, 12, 15–17, 19, 20, 22–25, 27, 29, 30, 32, 36–39, 41–50]. This is due to the use of a vacuum bag during the manufacturing process.

Some authors have tried to use different techniques to well-master the dimensions of the mechanical part. Bachmann and Delpero have used a closed mold in order to manufacture rotor blades by developing a Resin Transfer Molding (RTM) technique [34, 40]. Lachat *et al* have developed a similar technique by the injection of the resin between two glass plates [26]. As depicted in figure 6, Paradies *et al* have introduced a technique by autoclave using two cowl plates located under the vacuum bag to constraint the mechanical parts [14, 18].

4.5. Maximal temperature

For the thermosetting resins, the speed of cure depends on the quantity of the accelerator added to the polyester resin and to the hardener used with the epoxy resin. The temperature is certainly another important factor to accelerate the process. When the temperature increases, the hardening is speed up. For the thermoplastic resins, the temperature is the most

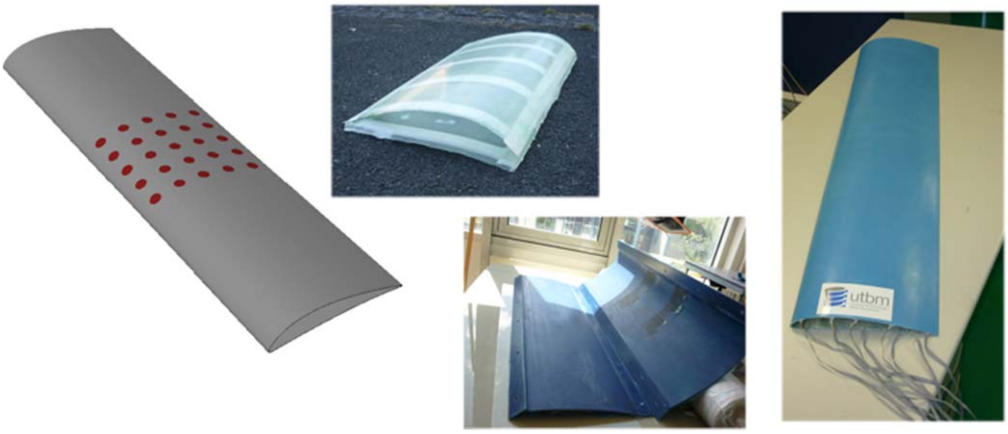

Figure 4. Active spoiler with 50 embedded piezoelectric transducers (reproduced with permission from[44]).

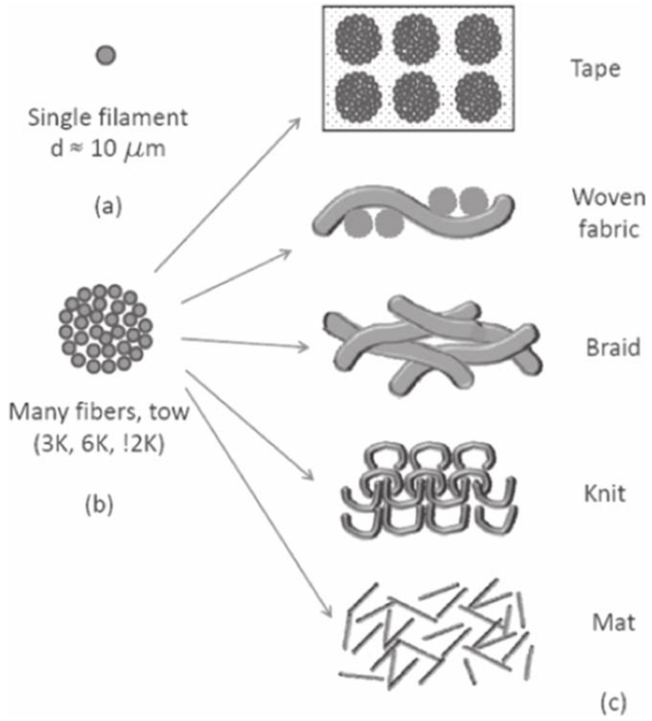

Figure 5. Fiber forms at different scales (reproduced with permission from[54]).

important factor to obtain a composite structure. The molding temperature has to be superior to the melting temperature of the semi-crystalline thermoplastic resins (i.e. PEEK) or superior to the glass transition temperature for the amorphous thermoplastic resins (i.e. Polyetherimide (PEI)). In this subsection, the designated temperature is either the maximum temperature during the curing and post-curing process for the thermosetting resins, or the maximum temperature during the processing of the thermoplastic resins. The idea is to evaluate the maximal temperature that the transducers can withstand during the manufacturing process. Based on figure 7, a division into four categories is adopted:

- Room temperature [26, 36–39, 41, 44, 46–49].
- Temperature <130 °C (60 °C [32], 75 °C [50], 80 °C [45], 120 °C [25, 35], 125 °C [31, 33, 42]).

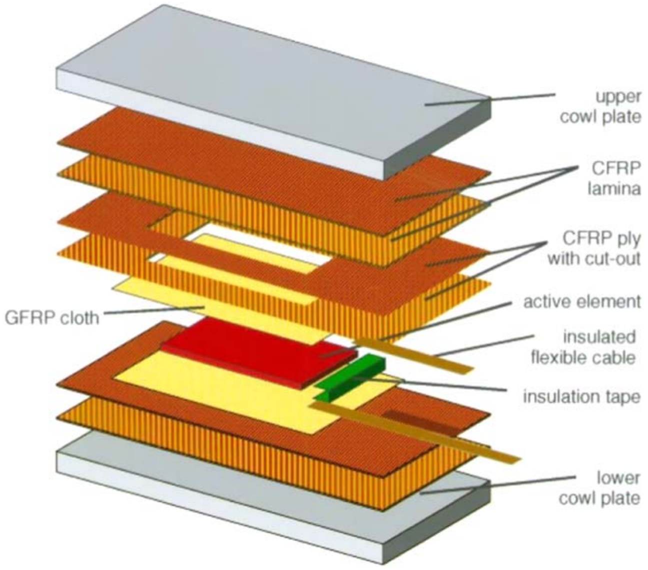

Figure 6. *In situ* lay-up for a piezoelectric actuator embedded into an electric conducting laminate [14, 18]

- Temperature around 180 °C (176 °C [15, 20, 23], 177 °C [5, 12, 13, 17, 19, 24, 30], 180 °C [7, 16, 22, 27, 29, 34, 40, 42]).
- Temperature >200 °C (230 °C [43], 288 °C [13], 325 °C [5], 371 °C [12, 13]).

When the maximal temperature is above 180 °C, the piezoelectric transducer can be dipoled. To avoid this problem, some authors have selected the piezoelectric material with a high Curie temperature (T_c), typically 350 °C. However, the effective depolarizing temperature can be below the Curie temperature [60]. In this case, the depolarizing temperature depends on the electric and mechanical stresses endured by the piezoelectric ceramics [61, 62]. This is the reason why $(Tc/2)$ is recommended as an empirical upper bound for the operating temperatures. Another way to manage this drawback is to perform a repolarization after the processing in order to guarantee the efficiency of the embedded transducers as depicted in figure 7. Several authors have

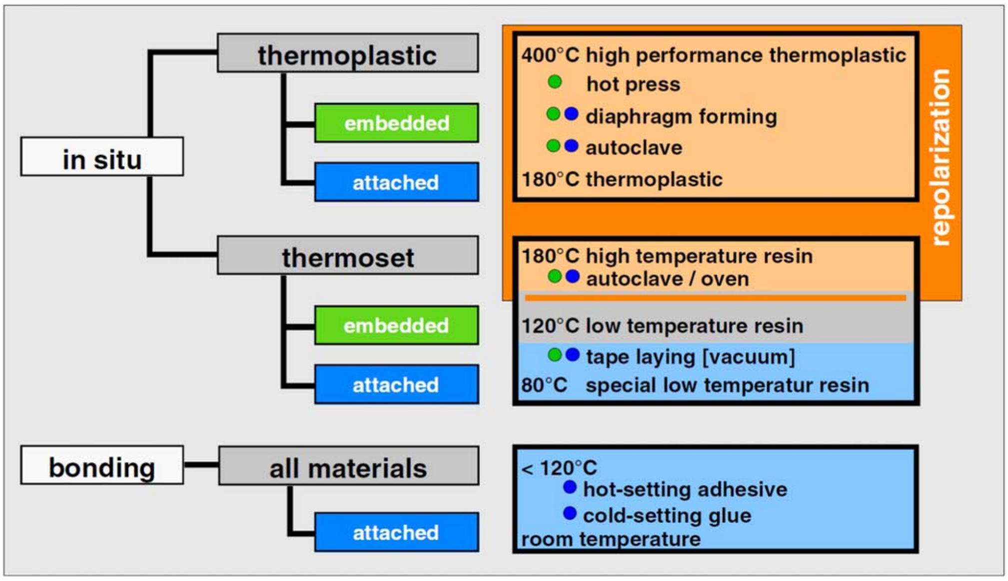

Figure 7. Manufacturing techniques for active structures with integrated piezoelectric elements (PZTs) [14, 18]

Table 3. Geometries and dimensions of embedded piezoelectric transducers in the literature.

Geometry	Diameter (mm)	Area (mm^2)	Thickness (mm)	Reference
Disk	6.35	—	0.254	[17, 19, 22, 24, 30]
Disk	10	—	0.2	[29]
Disk	20	—	0.2	[26]
Disk	25	—	0.135	[44, 48, 49]
Plate	—	30.1 × 9.7	0.07	[35]
Plate	—	- (no data)	0.125	[14, 18]
Plate	—	15.5 × 24.5	0.127	[25]
Plate	—	10 × 10	0.13	[16]
Plate	—	50 × 8	0.2	[28]
Plate	—	50 × 30	0.2	[28, 34, 40, 45]
Plate	—	- (no data)	0.25	[14, 18]
Plate	—	50.8 × 25.4	0.254	[15, 20, 23]
Plate	—	17.8 × 17.8	0.3	[27]
Plate	—	- (no data)	0.3	[14, 18]
Plate	—	36 × 36	0.5	[50]
Disk	5	—	0.5	[37–39, 41, 46, 47]
Disk	10	—	1	[36–39, 41]
Plate	—	50 × 30	1	[45]

considered this phase in the manufacturing process [12, 14, 15, 18, 20, 23, 43].

4.6. Applied pressure

The applied pressure on the structure is related to the compaction stage. In order to guarantee a good bonding between the matrix, the fibres and the transducers, and consequently the mechanical properties of the final structure, the volume ratio of the fibres is monitored to circumvent the voids and defects into the material. The higher the pressure, the better the compaction and the structural properties are. Since the piezoceramics are brittle and sensitive to the mechanical stresses, the maximal admissible pressure is an important data. Clearly, this value depends greatly on the selected manufacturing process. On the other hand, two main techniques are used to obtain the functional structures: the first using a vacuum process (infusion, VARTM,…) [32, 34, 37–41, 44, 46–49] and the second an autoclave process. In the second process, the laminate is vacuum-bagged then places in an autoclave. The maximal pressure in the autoclave is then analyzed. The typical bandwidth pressure vary between 1 and 7 bars (1 bar as in ref. [31, 33], 1.7 bars as in [5], 2.1 bars as in [5, 27], 3 bars as in [25], 5 bars as in [43], 6 bars as in [12, 16, 22, 29] and 7 bars as in [15, 20, 23, 42, 45]). When a hand lay-up method is selected [36], the ambient pressure is used. For filament winding [24, 30], Teflon tapes are used to compact the fibres. For the applications using RTM [26, 34, 40], no data are provided about the resin injection pressure.

4.7. Patch size

For patches, two standard geometries are used for the bulk piezoelectric transducers: a disk or a rectangular plate. The complex geometries for transducers are not exploited because of the difficulty to predict their final transducing behaviour. All the transducers have a high aspect ratio due to a low thickness with respect to the characteristic length. This low thickness is to limit the intrusivity of the piezoelectric implants with respect to the host composite structure. As detailed in table 3, in most cases, the transducer thickness is selected to be inferior to a ply thickness (typically ⩽0.3 mm). Few authors have embedded transducers with a thickness superior to 0.3 mm. The use of this option implies specific inclusion techniques in order to respect the technical requirement concerning the limitation of the thickness variations of the host structure. The surface area of all the transducers is quite limited in comparison to the area of the host composite structure. The objective here is to build complex shaped structures without stress concentrations resulting from local stiffening due to the piezoelectric implants.

4.8. Inclusion of the piezoelectric transducers

The importance of the embedding techniques is related to the way of including the bulk piezoelectric transducers inside the composite structure. These techniques are very critical in placing the transducer along the thickness-axis and into the composite structure. The easiest method is to directly place the transducer between two plies [14, 18, 26, 31–33, 37–39, 41, 43, 45–47]. For this, the transducer thickness has to be thin with respect to typical ply thickness. With this technique, the continuity of different plies is guaranteed. Resin pockets appearing at the transducer boundaries are depicted in figure 8. These resin pockets can create a structural weakness leading, for instance, to an initiation of delamination. Moreover, if the transducer location is not accurately defined, the piezoelectric element can move during the compaction and the resin will spread. Therefore, it is necessary to glue the transducer on a ply with a glue compatible with the resin. Another method is to use a ply with cut-out [5, 7, 12, 14, 15, 18, 20, 23, 36, 42, 45, 50]. The cut-out has to have the exact geometry of the transducer. As shown in figure 9, the volume of the resin pocket could be strictly limited and the structure thickness well mastered. However, some discontinuities may be generated in the fibre layer. Moreover, for complex structures, the geometry of the cut-out and the accurate positioning of the transducer can be difficult to achieve. Both of these techniques have another disadvantage.

They are well adapted for electrically insulated composite material but could be difficult to use in carbon fibre-reinforced composite structures which are naturally conductive. The use of semi-finished products can provide a good electric insulation hence solve other major disadvantages.

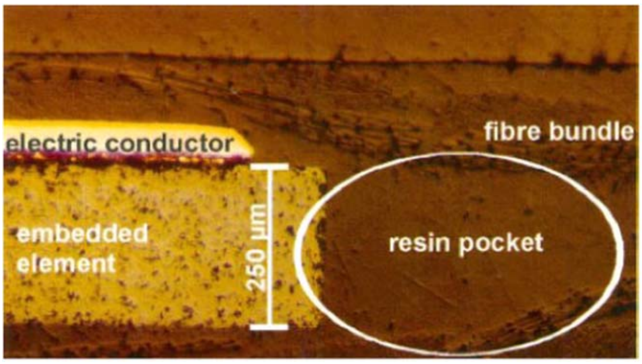

Figure 8. Cross-section of a completely embedded bulk piezoelectric element without a cut-out [14, 18]

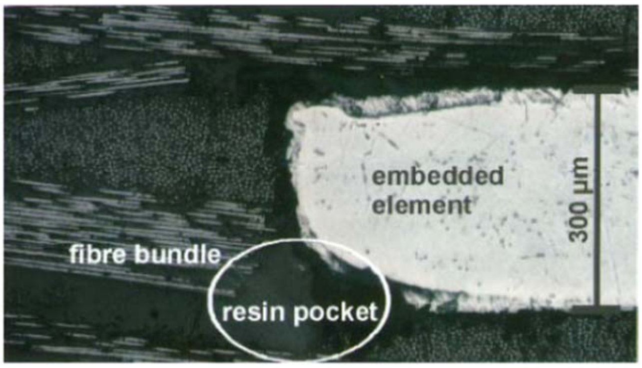

Figure 9. Cross-section of a completely embedded bulk piezoelectric element with a cut-out [14, 18]

In fact, the transducers are not anymore directly included during the manufacturing process: they are contained within two insulated layers. After impregnation, a semi-finished product is created during this supplementary manufacturing step. Then, this semi-finished product is embedded between two fibre layers. Moreover, the resin of the semi-finished product has to be compatible with the one of the final composite structure. Many authors have developed different types of semi-finished products. The first applications used a polyimide (Kapton) encapsulation [5, 16, 27–29, 34, 35, 40, 63]. Stanford University and its spin-off, Acellent Technologies, Inc. has developed a patented Stanford Multi-actuator-Receiver Transduction (SMART) Layer Technology [17, 19, 21, 22, 24, 30, 64–66] based on polyimide encapsulation. A GFRP composite with two plies has also being used to create a soft layer as a semi-finished product [14, 18, 25, 43, 44, 48, 49, 67]. Bronowicki *et al* have used an epoxy insulating medium [12]. With the semi-finished products, it is also possible to accurately guarantee that the final positioning of the transducer, with respect to the overall structure, will be realized and the relative positioning of the other transducers will also be achieved [67].

4.9. Electrical connection between the conductors and the transducer

The electrical connection between the conductors and the transducer is a key element of the embedding techniques. The reliability of the smart composite structures strongly depends on the quality and durability of these connections which have to resist the manufacturing process and the operating conditions of the final structure. The easiest way of obtaining these connections is to directly solder the electric conductors on the surfaces of the transducer [5, 12, 25, 26, 28, 31–33, 36–39, 41, 42, 46, 47, 50]. The volume and the positioning of the soldering points have to be mastered adequately because of the compaction step. In fact, if the soldering volume is excessive, the soldering point may act as a mechanical wedge. During the compaction, this wedge could break the piezoelectric transducer. In order to avoid this problem, some authors have developed other connection techniques. The wires can be directly bonded to the transducer with non-conductive glue [5, 7]. When using a semi-finished product with polyimide films, conductive tracks can be printed and connected to the transducers [17, 19, 21, 22, 24, 30, 64–66]. Thus a flexible circuit with piezoceramic transducers is created. Aluminum tapes [14, 18], wires [14, 18], copper tapes [27, 40, 43], copper foils [34, 40] or copper tracks [27, 40] could then be directly in contact with the transducer. The impregnation and compaction processes allow fixing the contact for the final application. The major drawback, particularly for tapes and foils, is the possible loss of electrical contact due to a flow of the non-conductive resin between both the conductive elements. In order to solve this shortcoming, a conductive woven fabric can be used to allow the contact between the transducer and the wires [44, 48, 49]. The porosity of the used fabric guarantees the validity of the electrical contact after impregnation and compaction. Lachat *et al* have embedded a piezoceramic transducer bonded on a brass disc of 30 mm diameter and 0.4 mm thickness [26]. The brass disc used has a ground electrode. The connection is obtained from the contact between the transducer and the wires during compaction. Paget and Levin [16] have used a conductive adhesive to obtain an electrical connection with the transducer while Salloum [45] have used a conductive adhesive copper foil to complete the electrical contact.

4.10. Input/output signals

The last point is to establish a robust link between the structure and its environment (power supply, control electronics, etc..). Most of the authors have used wires [5, 7, 14, 15, 18, 20, 23, 25, 26, 28, 31–33, 35–39, 41, 43, 44, 46–49] or printed circuit boards in polyimide substrate layer [17, 19, 21, 22, 24, 27, 29, 30, 64–66]. Copper foil electrodes or layers [16, 34, 40, 45] can also be used.

As shown in figure 10, a radio transceiver and an antenna can also be embedded in order to transmit the data [50]. In this system, the piezoelectric transducer, wired to a power management electronic circuit, supplies a microcontroller with a temperature sensor, a radio transceiver and an antenna. The piezoelectric transducer can also be coupled with a coil [42]. An inductive coupling between an inspection wand and the smart structure is used in order to transmit the data.

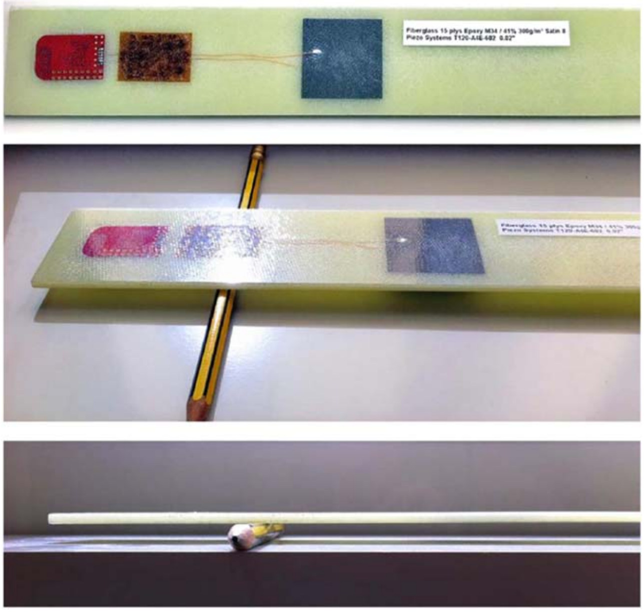

Figure 10. Integrated wireless structural monitoring system in GFRP beam (reproduced with permission from [50]).

5. Conclusion and future prospects

A review of the state-of-the-art and the state-of-practice of the manufacturing techniques of smart composite structures with embedded bulk piezoelectric transducers are presented. All the steps of manufacturing as well as the factors impacting the performance of the final products have been presented and fully explained.

One important facet of the smart composite structure is the intrusivity of the embedded piezoelectric elements which can modify the overall behavior of the structure. The fatigue resistance and the durability of these smart structures were investigated with respect to the type of selected embedding methods (cut-out, soft layer, …), the electrical connections, the fibre type, the matrix type, … On the other hand, some authors have investigated the intrusivity of passive implants with respect to different embedding conditions [68–70] and piezoelectric implants for one particular manufacturing process [37–39]. The main question is to find out if the risk-benefit ratio between the modification of the durability due to the implants and the new functions is favorable and what influence can the selected manufacturing process have on this ratio.

Figure 2 indicates that the manufacturing techniques to transform the smart composite structures into mass-market products manufactured for large production have not been

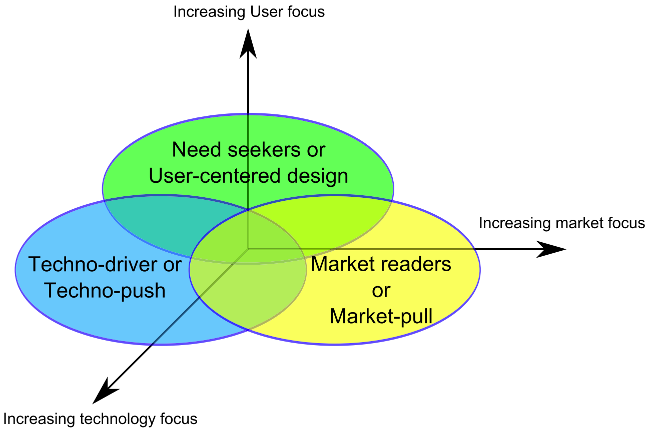

Figure 11. Three innovation approaches.

investigated yet. Some authors [71, 72] have tested the manufacturing of smart composite structures with an injection molding process or thermoforming with success but for a structural application. Consequently, the question is still wide open to find out if the actual smart structures can be only prototypes or will soon become mass-production products with great potential applications.

Since the mid-1980's, the main applications were dealing with vibration control, structural health monitoring, energy harvesting and shape control. The development of new applications can be obtained by investigating new innovation process. As depicted in figure 11, three main strategies of innovation are proposed. The first strategy is the **Techno push or Techno Driver** which consists of developing a new approach to generate new applications. Many users/costumers have adopted this innovative approach because of its technological advance. This involves heavy investments in research and development. The second **strategy Market pull or Market Reader** consists of evaluating the current competitive landscape, the market and the customers to spot emerging opportunities and value creation ideas. This strategy is widely used in industrial companies. Finally, the third strategy **Need Seekers** consists of involving the customer and understanding unmet or unarticulated needs in order to design and deliver products that meet all these needs. This last question seems interesting to investigate: What user-centered design methods and tools can be implemented to identify new uses, new applications, and new products based on technological bricks? To answer this question, some specific steps of user centered design approach should be applied such as, for instance, the use of the creativity sessions. As shown in figure 11, these three strategies can be combined in order to greatly impact the success of an innovation. These new applications could significantly impact the development of the manufacturing techniques.

In the industrial field, the goals to save energy, in particular via mass reduction, have been conducted using composite structures. The growth of global production (around 11 millions of tons per year [73]) generates more and more wastes from production and from the disposal of the end-of-life products. The GFRPs dominate the composites market with more than 90% of the global volume production [74] and 70% of the manufactured composite structures is made of thermosetting resins [75]. It is important to evaluate the opportunities given by the composite materials to reduce the product environmental impact comparatively to standard materials [76] because their sustainability is always in question [77]. Currently, the only operational tool is the life cycle assessment [78]. Beyond the purely technical problems posed by the currently industrial recycling methods (crushing for fibreglass composites or pyrolysis for carbon fibre composites), it is also interesting to evaluate the influence of the fibre brand [79], the matrix type, the manufacturing process [80] and the recycling method [81] on the environmental indicators. By extension, all these questions have to be applied to the smart composite structures. Another question is to find out if these new functions in terms of vibration control and structural health monitoring have an impact on the environmental indicators. For instance, embedding piezo-transducers into a natural fibre based composite structure could increase its service life and its environmental indicators. This embedding could also help detect the damage during the functioning process and thus increase the functionality of the product [82]. Moreover, 80% of the environmental impact of a product over its life cycle is determined during the design phase [83]. It seems important to investigate the way smart composite structures are well-designed by developing specific design process in particular for the early design stages and for the operational design rules [84]. It is also possible to take advantage of this design process to promote an environment approach to product design [85].

From a technological point of view, some of these aspects can be seriously investigated. For instance, the robust link between the structure and its environment is widely achieved with wires. It should be interesting to develop manufacturing techniques to implement directly a physical connector on the surface of the smart composite structures. As proposed by Lampani and Gaudenzi [50], the development of embedded self-powered wireless smart implants for specific applications seems to be an interesting research axis.

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