1 Historical Developments and Potential Applications: Smart Materials and Structures

The quest for superior capability in both civil and military products has been a key impetus for the discovery of high performance new materials. In fact, the standard of living has been impacted by the emergence of high performance materials. There is no doubt that the early history of civilization is intertwined with the evolution of new materials. For example, different eras of civilization are branded with their material capabilities, and these periods are referred to as the Stone Age, the Bronze Age, the Iron Age, and the Synthetic Material Age. The Stone Age represents the earliest known period of human civilization that stretches back to one million years BC, when tools and weapons were made out of stone. The Bronze Age (sometimes called the Copper Age) spans 3500–1000 BC. Weapons and implements were made of bronze (an alloy of copper and tin) during this period. The alloy is stronger than either of its constituents. Bronze was used to build weapons such as swords, axes, and arrowheads; implements such as utensils and sculptures; and other industrial products. The Iron Age followed the Bronze Age around 1000 BC and was characterized by the introduction of iron metallurgy. Iron ores were plentiful (cheap) but required high-temperature (2800°F) furnaces as compared to copper, which required lower-temperature (1900°F) furnaces. The Iron Age was the age of the industrial revolution, and many of the initial design tools, mechanics-based analyses, and material characterizations were formulated during this period. The Synthetic Material Age started in the early part of the twentieth century with the development of a wide range of man-made synthetic materials. This era saw an explosion of technological developments that touched every phase of human endeavor. Most of the high-performance engineering products, such as aerospace, computers, telecommunication, and medical and power systems, were the result of the development of advanced materials. This was an era of consolidation in terms of the development of comprehensive design tools, material characteristics, and mechanics-based analyses. During this period, the aerospace industry pioneered the development of composite materials and structures that had direct impact on structural capability (e.g., specific strength and specific stiffness) as well as manufacturing and maintenance costs. This translated into an increase in performance, payload, speed, range and a reduction in life-cycle cost.

The twenty-first century may be visualized as the Multifunctional Materials Age. The inspiration for multifunctional materials comes from nature; hence, these are often referred to as "bio-inspired materials." This category encompasses smart materials and structures, multifunctional materials, and nano-structured materials. This is a dawn of revolutionary materials that may provide a "quantum jump" in performance and multi-capability. This book focuses only on smart materials and structures. These are also referred to as intelligent, adaptive, active, sensory, and metamorphic structures and materials and/or systems. The purpose of these materials from the perspective of smart systems is their ability to minimize life-cycle cost and/or expand the performance envelope. The ultimate goal is to develop biologically inspired multifunctional materials with the capability to adapt their structural characteristics (e.g., stiffness, damping, and viscosity) as required, monitor their health condition, perform self-diagnosis and self-repair, morph their shape, and undergo significant controlled motion over a wide range of operating conditions.

Since the 1990s, there has been a major growth in smart structures technology, in both individual technological constituents and their applications in various disciplines. Applications include vibration and noise suppression, stability and damping augmentation, shape control, structural integrity monitoring, and condition-based maintenance. Relevant disciplines include space vehicles, fixed-wing aircraft, rotary-wing aircraft, civil structures, marine systems, automotive systems, robotic systems, machine tools, and medical systems. Major goals have been to enhance system performance (beyond current levels) at a low cost, increase comfort level (minimize noise and vibration) with minimum weight penalty, reduce life-cycle cost (decrease vibratory loads and perform condition-based maintenance), improve precision pointing (space telescope), improve low observable characteristics, and increase product reliability (damage detection, mitigation, and repair).

Development of smart materials and structures is possible through one of three approaches. In the first approach, the new materials with smart functionality can be synthesized at the atomic and molecular levels. Sometimes this is referred to as a nano-structured material. A lot of the relevant methodology is hypothesized and is in an embryonic state at this time. In the second approach, actuators and sensors are attached to a conventional structure that adaptively responds to external disturbances. The actuators and sensors normally do not constitute the load-carrying structure. Even though this is a relatively mature methodology, it is not expected to be a structurally efficient scheme. In the third approach, active plies representing actuators and sensors are synthesized with non-active plies to form a laminated structure. A major drawback is that once the structure is cured, it is not possible to replace nonfunctional plies. Even though this approach appears attractive in terms of structural efficiency, there are issues related to the integrity of the system.

The key elements of smart structures are actuators, sensors, power conditioning, control logics, and computers. Conventional displacement actuators are electromagnetic (including voice coils), hydraulic, and servo- or stepper motors. The principal disadvantages of conventional actuators are their weight, size, and slow response time. Their advantages are their large stroke, reliability, familiarity, and low cost. Smart material actuators are normally compact and change their characteristics under external fields such as electric, magnetic, and thermal. Typical smart material actuators are piezoelectric, electrostrictive, magnetostrictive, shape memory alloys, and electrorheological/magnetorheological (ER/MR) fluids. Conventional sensors are strain gauges, accelerometers, and potentiometers, whereas smart material sensors can be fiber optics, piezoelectrics (ceramics and polymers), and magnetostrictives. There is a wide variation of power requirements for different actuators. Key factors for a power conditioning system are compactness, efficiency, and cost. For an efficient adaptive system, the modeling and implementation of robust feedback control strategies are important. A centralized, compact, and lightweight computer is vital to generate input signals for actuators, perform system identification techniques with output data from sensors, and implement control-feedback strategies.

The basic idea of the synthesis of smart structures appears to have been first conceptualized by Clauser in 1968 [1]. Seven years later, Clauser himself demonstrated the concept [2]. After this work, activity in this area started increasing and grew rapidly in the 1990s.

The historical development of key smart materials is discussed first, followed by their applications in various industrial disciplines. Even though the discovery of many of the smart materials took place during the past century, the commercial availability, cost, and understanding of their behavior have been major impediments to their widespread use in commercial products. Today, one of the most popular smart materials is polycrystalline piezoceramic, which exhibits strong piezoelectric properties. Other popular smart materials include electrostrictives, magnetostrictives, shape memory alloys, and ER/MR fluids.

1.1 Smart Structures

A smart structure involves distributed actuators and sensors as well as one or more microprocessors that analyze the responses from the sensors and use integrated control theory to command the actuators to apply localized strains or displacements to alter system response. A smart structure has the capability to respond to a changing external environment (e.g., load or shape change) as well as to a changing internal environment (e.g., damage or failure). It incorporates smart material actuators that allow the alteration of system characteristics (e.g., stiffness or damping) as well as of system response (e.g., strain or shape) in a controlled manner. Thus, a smart structure involves five key elements: actuators, sensors, control strategies, power- and signal-conditioning electronics, and a computer. Many types of actuators and sensors, such as piezoelectric materials, shape memory alloys, electrostrictive materials, magnetostrictive materials, ER/MR fluids, and fiber optics, are being considered for various applications. These can be integrated with main load-carrying structures by surface bonding or embedding without causing any significant changes in the mass or structural stiffness of the system.

Numerous applications of smart structures technology to various physical systems are evolving to actively control vibration, noise, aeroelastic stability, damping, shape change, and stress distribution. Applications range from space systems to fixed-wing and rotary-wing aircraft, automotive, civil structures, machine tools, and medical systems. At this time, servovalve hydraulic actuators are widely used in aerospace and other applications because of their reliable performance across a large range of force, stroke, and bandwidth. Their drawbacks, such as mechanical complexity, need for hydraulic tubing and reservoir, and size and weight, present an opportunity to search for lightweight compact actuators such as smart material actuators. A "smart material" is defined as a material that transforms its characteristics, such as mechanical states (strain, position, or velocity) or material characteristics, (stiffness, damping, or viscosity) under external field (electric, magnetic, or thermal). Much of the early development of smart structures methodology was driven by space applications such as vibration and shape control of large flexible space structures, but now wider applications are envisaged for aeronautical and other systems.

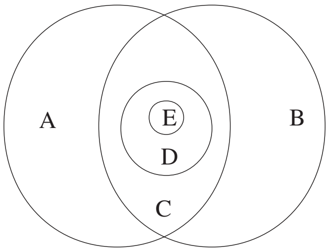

Figure 1.1. Classification of smart structures.

Embedded or surface-bonded smart actuators on an airplane wing or a helicopter blade, for example, can induce airfoil twist/camber change that in turn can cause a variation of lift distribution and may help control static and dynamic aeroelastic problems.

Applications of smart structures technology to aerospace and other systems are expanding rapidly. Major barriers include low actuator stroke, the lack of a reliable smart material characteristics database, nonavailability of robust distributed adaptive control strategies, and inadequate mathematical modeling and analysis of smart systems.

A smart or intelligent structure incorporates distributed actuators and sensors as well as control logic, processors, and power electronics. Figure 1.1 defines various types of structures, as follows:

Adaptive Structures (A): have distributed actuators to alter characteristics in a prescribed manner. They may not have sensors. Examples are conventional aircraft wings with flaps and ailerons, and rotor blades with servoflaps.

Sensory Structures (B): have distributed sensors to monitor the characteristics of the structure (i.e., health monitoring). Sensors may detect strain, displacement, acceleration, temperature, electromagnetic properties, and extent of damage.

Controlled Structures (C): overlap both adaptive and sensory structures. These constitute actuators, sensors, and a feedback control system to actively control the characteristics of the structure.

Active Structures (D): are a subset of controlled structures. Integrated actuators and sensors have load-carrying capability (i.e., structural functionality).

Intelligent or Smart Structures (E): are a subset of active structures. Additionally, they have highly integrated control logic and power electronics.

1.1.1 Smart Material Actuators and Sensors

Piezoelectrics are the most popular smart materials. They undergo deformation (strain) when an electric field is applied across them and, conversely, produce voltage when strain is applied; thus, they can be used as both actuators and sensors. Under an applied field, these materials generate a very low strain but cover a wide range of actuation frequency. Piezoelectric materials are relatively linear (at low fields) and bipolar (positive and negative strain) but exhibit hysteresis. To achieve high actuation force, piezoceramics (ferroelectric ceramic materials) are used. The most widely used piezoceramics (e.g., lead zirconate titanate, or PZT) are mostly available in the form of thin sheets that can be readily attached or embedded in

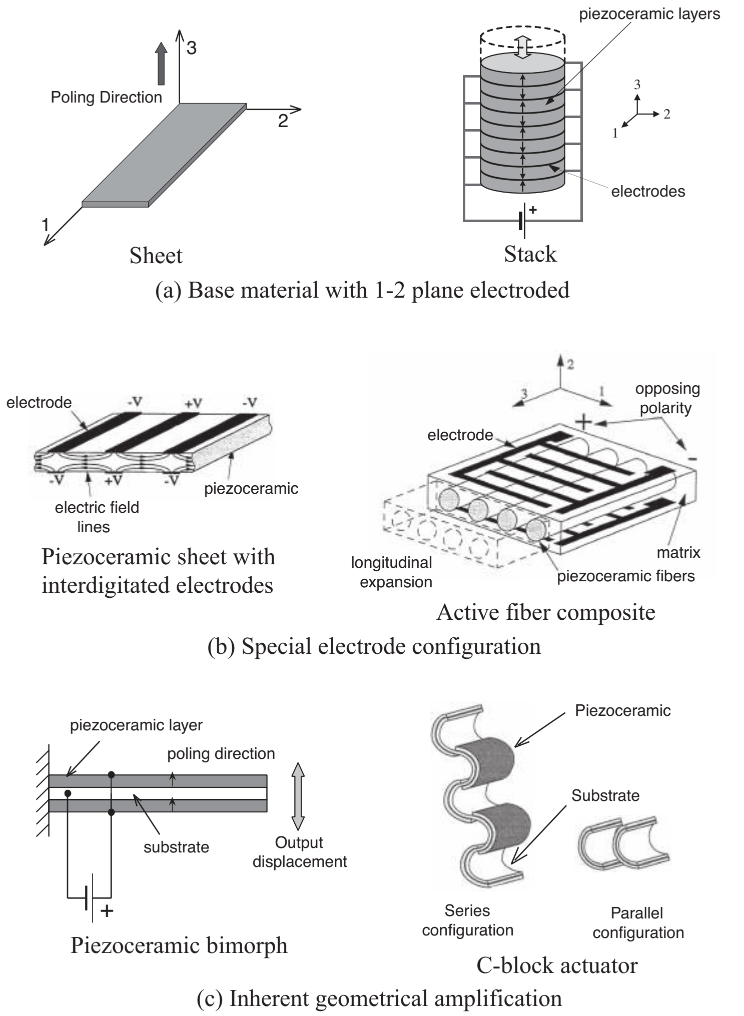

Figure 1.2. Typical piezoceramic actuators.

composite structures or stacked to form discrete piezostack actuators (Fig. 1.2). These sheets generate isotropic strains on the surface and a non-Poisson strain across the thickness. It is possible, however, to generate directional in-plane induced strains with piezoceramics using electrode arrangement, specially shaped piezos, bonding arrangement, and embedded fibers (see Fig. 1.2). Electrostrictives such as lead magnesium niobate (PMN) also require electric field to cause induced strain and have about the same induced-strain capability as piezoelectric materials. However, they are a nonlinear function of field (typically varying quadratically with field) and monopolar. Also, electrostrictive materials are very sensitive to temperature but exhibit negligible hysterisis.

Piezoelectric and electrostrictive materials are also available in the form of "stacks," in which many layers of materials and electrodes are assembled together. Typically, stacks are built using one of two methods. In the first method, the sheets of active material and electrodes are bonded together using an adhesive (normally of lower stiffness than the active material). In the second method, the layers of active material and the electodes are co-fired in the presence of high isostatic pressure. The stacks generate large forces but small displacements in the direction normal to the top and bottom surfaces. Piezostack actuators are further divided into two categories: low-voltage devices (about 100 volts) and high-voltage devices (about 1000 volts). Since the maximum electrical field for PZT is on the order of 1 to 2 kV/mm, low-voltage devices consist of 20 to 100 μm thickness sheets and high-voltage devices consist of 0.5 of 1.0 mm thick sheets. Bimorphs or bending actuators are also available commercially, in which two layers of these materials (piezoceramic) are stacked with a thin shim (typically of brass) between them. If an opposite polarity is applied to two sheets, a bending action is created. Bimorphs cause larger displacement and smaller force as compared to single piezo elements. The bending displacement is the highest at the tip of the cantilevered bimorph actuator. To increase the actuation force, multilayered bimorphs (or multimorphs) are used.

Among other smart materials, shape memory alloys (SMA) appear attractive as actuators because of the possibility of achieving large excitation forces and displacements. These materials undergo phase transformation at a specific temperature. When plastically deformed at a low temperature, these alloys will recover their original undeformed condition if their temperature is raised above the transformation temperature. This process is reversible. A remarkable characteristic of SMA is its large change of modulus of elasticity when heated above phase transformation temperature (typically two to four times the low temperature value). The most common SMA material is Nitinol (nickel titanium alloy), which is typically available in the form of wires of different diameters. Heating of an SMA can be carried out both internally (electrical resistance) and externally (using heating coils), but the response is very slow (less than 1 Hz). It is sometimes possible to speed up the response through forced convective or conductive cooling of material. Magnetostrictive materials such as Terfenol-D elongate when exposed to a magnetic field. These materials are monopolar and nonlinear, and they exhibit some hysteresis (less than piezoelectric). These materials generate low strains and moderate forces across a wide frequency range. Because of the required coil and magnetic return path, these actuators are often bulky. Electrorheological (ER) fluid consists of suspensions of fine dielectric particles in an insulating fluid that exhibits controlled rheological behavior in the presence of large applied electric fields (up to 1–4 kv/mm). Application of an electric field results in a significant change of shear-loss factor (fluid viscosity) that helps alter damping of the system. Magnetorheological (MR) fluid consists of suspensions of ferrous particles in fluid and exhibits change in shear-loss factor due to magnetic fields (low fields but moderately large currents). MR fluids, like ER fluids, are primarily envisaged as augmenting damping in a system. Fiber optics are becoming popular as sensors because they can be easily embedded in composite structures with little effect on structural integrity, and they also have the potential of multiplexing.

Smart structures are becoming feasible because of the (1) availability of smart materials commercially, (2) ease of embedding devices in laminated structures, (3) exploitation of material couplings such as between mechanical and electrical properties, (4) potential of a substantial increase in performance at a small price (e.g., weight penalty), and (5) advances in microelectronics, information processing, and sensor technology. Key elements in the application of smart structures technology to a system are actuators, sensors, control methodology, and hardware (computer and power electronics).

Table 1.1. *Comparison of actuators*

Actuators	Piezoceramic PZT	Piezofilm PVDF	Electrostrictive PMN	Magnetostrictive Terfenol-D	Shape Memory Nitinol
Ferroic class	Ferroelectric	Ferroelectric	Ferroelectric	Ferromagnetic	Ferroelastic
Field	Electric	Electric	Electric	Magnetic	Thermal
Maximum Free Strain %	0.1	0.07	0.1	0.2	8
Response time	μs	μs	μs	μs	s
Young's Modulus E (GPa)	68.9	2.1	117.2	48.3	27.6 for martensite 89.6 for austenite
Strain-voltage characteristic	First-order linear	First-order linear	Nonlinear	Nonlinear	Nonlinear

1.1.2 Smart Actuators

Typical actuators consist of piezoceramics, magnetostrictives, electrostrictives, and shape memory alloys. These normally convert electric/magnetic/thermal inputs into actuation strain/displacement that is transmitted to the host structure, affecting its mechanical state. Piezoelectrics and electrostrictors are available as ceramics, whereas magnetostrictors and shape memory alloys are available as metal alloys. Piezoelectrics are also available in polymer form as thin soft film. Important performance parameters of actuators include maximum stroke or strain (free condition), maximum blocked force (restrained condition), stiffness, and bandwidth. Somewhat less important parameters include linearity, sensitivity to temperature, brittleness and fracture toughness (fatigue life), repeatability and reliability, power density, compactness, heat generation, field requirement, and efficiency. The induced strain is often treated like thermal strain. The total strain in the actuator is assumed to be the sum of the mechanical strain caused by the stress plus the induced strain caused by the electric field. The strain in the host structure is obtained by establishing the displacement compatibility between the host material and the actuator. In a piezoelectric material, when an electric field is applied, the dipoles of the material try to orient themselves along the field, causing strain in the material. This relation of strain versus voltage is linear to the first order. In an electrostrictive material, there is an interaction between the electric field and electric dipoles, which is inherently nonlinear. The magnetostrictive response is based on the coupling of magnetic field and magnetic dipoles in the material, again a nonlinear effect. Shape memory is a result of phase transformation due to temperature change of the material (caused by a thermal field). Phase transformation is very much a nonlinear phenomenon.

A common piezoceramic material is lead zirconate titanate (PZT), and its maximum actuation strain is about one-thousand microstrain. Polyvinylidenefluoride (PVDF) is a polymer piezoelectric film and its maximum actuation strain is about seven-hundred microstrain. A common ceramic electrostrictive material is lead magnesium niobate (PMN) and its maximum actuation strain is about one-thousand microstrain. PZT and PMN are available in the form of thin sheets, which can be either bonded or embedded in a structure.

The PZTs require initial polarization (with high electric field), whereas no such polarization is needed for PMNs. Terfenol, a rare earth material, can create a maximum actuation strain of about two-thousand microstrain. It needs a large magnetic field in the axial direction to cause this actuation strain. Nitinol (nickel titanium alloy), normally available in the form of wires, can create free strain from 20,000 to 60,000 microstrain (2–6%). Table 1.1 shows a comparison of characteristics for

Table 1.2. *Comparison of sensors*

Sensor	Resistance gauge 10 V excitation	Semiconductor gauge 10 V excitation	Fiber Optics 0.04″ interferometer gauge length	Piezofilm 0.001″ thickness	Piezoceramics 0.001″ thickness
Sensitivity	30 V/ε	1000 V/ε	10^6 deg/ε	10^4 V/ε	2×10^4 V/ε
Localization (inches)	0.008	0.03	0.04	<0.04	<0.04
Bandwidth	0 Hz-acoustic	0 Hz-acoustic	0 Hz-acoustic	0.1 Hz-GHz	0.1 Hz-GHz

different smart actuators. Giurgiutiu et al. [3] compared the characteristics of various commercially available piezoelectric, electrostrictive, and magnetostrictive actuators. The comparison was carried out in terms of output energy density. Typically, the energy density per unit mass was found to be in the range of 0.233 to 0.900 J/kg. There is a wide variation in the performance of actuators among manufacturers. Near [4] provided an overview on piezoelectric actuator technology.

1.1.3 Sensors

Typical sensors consist of strain gauges, accelerometers, fiber optics, piezoelectric films, and piezoceramics. Sensors convert strain or displacement (or their time derivatives) into an electric field. Resistance (foil) and semiconductor strain gauges depend on a change of resistance due to the strain, and these require a DC excitation field for measurement. Piezoceramics and piezofilms are based on the variation of piezoelectric charge generated as a result of change in strain, and these do not require any external field. Fiberoptic gauges rely on a mechanical/optical coupling effect where output is expressed in terms of the phase lag of a monochromatic wave passed through the fiber as a result of the strain.

Piezoelectric strain sensors are generally made of polymers such as PVDF, and are very flexible (low stiffness). They can be easily formed into very thin sheets (films) and adhered to any surface. Key factors for sensors are their sensitivity to strain or displacement, bandwidth, and size. Other less important factors include temperature sensitivity, linearity, hysteresis, repeatability, electromagnetic compatibility, embeddability, and associated electronics (size and power requirement). Typically, the sensitivity for a resistor gauge is approximately 30 volts per strain; for a semiconductor gauge, it is 10^3 volts per strain; and for piezoceramic gauges, it is 10^4 volts per strain. The sensitivity of fiber-optic sensors is defined differently and is about 10^6 degrees per strain. Associated electronics may weigh against fiber-optic sensors. Discrete shaped sensors that apply weighting to the sensors' output can help increase sensitivity for a specific application. For example, a modal sensor can magnify the strain of a particular mode. Table 1.2 shows a comparison of characteristics of different sensors for typical excitation voltages, gauge lengths, and sensor thicknesses.

1.1.4 Actuator-Sensor Synthesis

In some cases, the same device can be used simultaneously as both an actuator and a sensor. This is referred to as self-sensing actuation and can be quite advantageous for active control applications because actuation and sensing actions are perfectly collocated [5]. For example, the piezoelectric material can be considered as a transformer between the structural states (stress and strain) and the electric states (voltage and charge). A piezoelectric self-sensing actuator can be created by incorporating two identical piezoelectric elements in a bridge circuit. The objective is to identify the difference in the charge components created by the applied electric field and the mechanical strain. Actuation force can be in the form of force, moment, or distributed strain, and sensing can be in the form of displacement, slope or strain, and their derivatives. For example, displacement, velocity, and acceleration are three separate output components. Hence, there can be a total of nine sensor output components and three force input components. Gupta et al. [6] outlined six criteria for optimal placement of piezoelectric actuators and sensors. These included (1) maximizing modal forces/moments, (2) maximizing deflection of the host structure, (3) minimizing control effort, (4) maximizing degree of controllability, (5) maximizing observability, and (6) minimizing spillover effects. It is important to place piezoelectric actuators in the region where the average modal strains are highest, which would result in maximum modal forces/moments. Placing actuators at the antinodes results in maximum deflection. It is advisable to place sensors at locations where the observability can be maximized. Boundary conditions also play an important role in the optimal placement of actuators and sensors.

1.1.5 Control Methodologies

For smart material applications, distributed control functionality is a key ingredient. There are three levels of control strategies: local control, global control, and higher cognitive functions. In local control, the objectives can be to augment damping, absorb energy, and minimize residual displacements. The objectives of global control can be to stabilize structural response, control shape, and minimize disturbances. The objectives of cognitive functions could be the ability to diagnose component failure and reconfigure and adapt after failures.

In the case of a system with single input and single output, local control can be established through a transfer function. The phase and amplitude of input actuation are adjusted to minimize the single output. Local control is used for adding damping and for low authority control. For the global control, there are several limiting cases of distributed control. The first one is a centralized controller in which the output from all sensors are processed by a centralized processor that provides control outputs to the distributed actuators. The second one is a decentralized controller in which the local control is carried out in an independent manner. However, it is computationally inefficient. Conversely, in the centralized controller, the computer has to process signals at rates corresponding to the highest mode of interest. To avoid these issues, one can arrive at a compromise controller straddling the two approaches of completely centralized and completely decentralized controllers – this is referred to as hierarchical or multilevel control architecture. This control strategy features a centralized controller for overall performance and a distributed processor for localized control. An average response within each element is then passed on to the global processor. This approach appears quite practical for many applications [7].

1.2 Manufacturing Issues

There are several issues concerning building of smart structures. These are as follows:

1. Electrical contact on both sides of the piezo is required. One way to overcome this problem can be to drill a hole in the substructure and use conducting epoxy. The second way is to introduce a thin layer of conductor between the piezo and the substructure and use a conducting bond layer.
2. The piezo has to be insulated from the structure. By anodizing or coating the structure, this problem can be solved.
3. For proper transfer of induced strain to main structure, bond-layer thickness needs to be thin and uniform. For this, pressure is applied during curing.

Embedding versus Surface-Mounting: With surface-mounted actuators, there is an ease of manufacturing, access for inspection, and less maintenance cost. Because of exposure, the actuators are more susceptible to damage. Also, the functioning of the actuators is dependent on the structural surface. With embedded actuators, the piezo becomes inaccessible for inspection. The devices, however, are better protected and interconnections with other devices become easy.

Embedding Electronics: For embedding integrated circuits, it is essential to ensure their electrical insulation and mechanical isolation. For minimal degradation of structure, it is important to have minimum ply interruption.

1.3 Piezoelectricity

Pierre and Paul-Jacques Curie (Fig. 1.3) discovered in 1880 (at the Sorbonne, France) that some crystals (e.g., Rochelle salt, topaz, tourmaline, cane sugar, quartz, sodium chlorate, and zinc blende), when compressed in certain directions, produce electric charges (positive and negative) on specific parts of their surfaces. The electric charges were found to be proportional to the applied pressure and vanished when pressure was removed. Furthermore, if the sign of pressure or strain was changed (e.g., from compression to tension), the developed charges also changed sign. This phenomenon was subsequently named, piezoelectricity, (pressure electricity, as piezo is a Greek word meaning "to press"). Piezoelectricity is different from contact and friction electricity. This effect of generation of charges due to applied pressure or stress is referred to as the "direct effect." In piezoelectric materials, there is also a "converse effect" (sometimes referred to as reciprocal or inverse effect) wherein a strain (or deformation) is caused in the material when it is exposed to an electric field. Again, induced strain is proportional to applied electric charge (polarizing field). The converse effect in piezoelectric crystals was first mathematically predicted by Lippmann in 1881 using fundamental laws of thermodynamics, and the Curie brothers experimentally demonstrated it in the same year. To demonstrate this, flat plates were cut according to a specific crystal orientation and surface bonded with tin foils as electrodes. For thirty years following its invention, until the First World War, piezoelectricity remained a scientific curiosity. Then there was a spurt of research activities in piezoelectricity, especially for applications in underwater ultrasonic detection. Using the converse effect, quartz and Rochelle-salt plates were excited at high frequencies (in the range of one megaHertz) to produce high-frequency sound waves for underwater detection. Paul Langevin and his co-workers in France developed ultrasonic