

# 2.33

## Life Cycle Engineering of Composites

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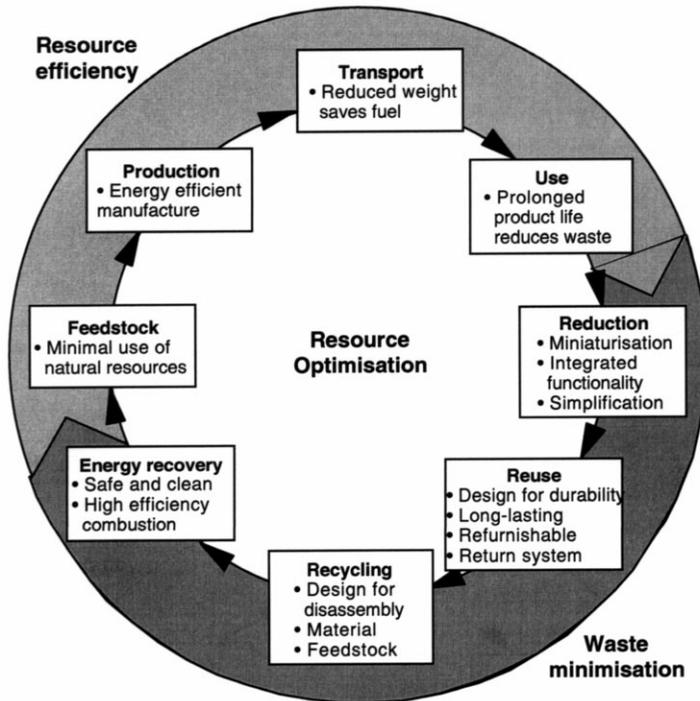
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**2.33.1 INTRODUCTION TO LIFE CYCLE ENGINEERING**

For decades, the development of polymer composites has been driven almost exclusively by performance criteria such as high specific stiffness. It is only in recent years that life cycle considerations have become prominent features in the design of composite-based products, with a gradual increase of recycling efforts, and growing interest for durability analyses. The issues of loop-closing, resource efficiency, waste reduction, and life-extension are to be seen as many facets of the life-cycle engineering concept, developed as an integrated method to design, manufacture, use, and recover materials and products for optimal

resources turnover, “from cradle to cradle,” as sketched in Figure 1. Much effort is nevertheless required to link product design to composite science and technology, and to environmental science: “recyclable” does not necessarily imply “recycled,” and “recycled” does not necessarily imply “environment-friendly.” This work is, therefore, an attempt to provide rational understanding of the key factors involved in such interplay.

This section introduces the overall framework for life cycle engineering. It establishes links to the underlying issue of sustainable resource management and emphasizes the need for durability analyses of composites. It also defines the main routes towards loop-closing and sets the main priorities in life cycle



**Figure 1** Life cycle engineering addresses both resource efficiency and waste minimization, in order to optimize resource intensity during the whole life cycle (adapted from Lundquist *et al.*, 2000; APME, 1999).

**Table 1** Material intensities (MI) of abiotic resources (i.e., nonrenewable) and water needed to produce selected materials (extract from Wuppertal Institute database Version 1.3c). The values do not include transport-related MI.

<i>Material</i>	<i>MI abiotic resources</i> (t/t)	<i>MI water</i> (t/t)
Fiber-reinforced composite	2.91	49.1
Kaolin	3.05	2.50
E-glass fiber	6.22	94.5
Aramid fiber	37.0	940
Carbon fiber	61.1	2411.5
Polyethylene	5.40	64.9
PVC	8.02	118
Polyester thermoset	5.40	209
Epoxy resin	13.7	290
Aluminum (primary)	85.4	1380
Aluminum (secondary)	3.45	60.9
Steel	6.35	46.8
Diamond	5 260 000	–

**Table 2** Markets for glass-fiber reinforced composites.

<i>Application field</i>	<i>Market shares<sup>a</sup></i> (%)	<i>Lifetime</i> (years)
Consumer goods	12	1–10
Electrical industry	19	5–50
Industrial equipment	20	5–50
Transportation	21	10
Building	16	> 30
Others	12	–

Source: Bowen, 1994

<sup>a</sup> Total world market 1986: 10 Mtons; projected market 2000: 100 Mtons.

engineering. The subsequent sections are organized as follows: Section 2.33.2 reviews the influences of the life cycle on the durability of polymer composites; Section 2.33.3 describes the main approaches for product design in the context of life cycle engineering; Section 2.33.4 describes state-of-the-art recycling processes for polymer composites; Section 2.33.5 introduces the life cycle assessment methodology, with case studies. Finally, Section 2.33.6 closes the various topics discussed in the preceding sections.

### 2.33.1.1 Sustainable Resource Management

For centuries, human activities have grown based on a linear economy, considering unlimited resources and an infinite sink to absorb all wastes. Worldwide efforts are underway to reduce the large imbalance in resource productivity, in the global context of sustainable development (see, for instance, WCED,

1988, Weizsäcker *et al.*, 1997, Gardner and Sampat, 1998). This imbalance is expressed as the ratio between the amount of resources and the weight of materials and products, thoroughly studied by the Wuppertal Institute and termed material intensity (MI) (e.g., Schmidt-Bleek, 1993). Table 1 reports several MI values for composite constituents, together with several other materials. It is evident that for all materials, the MI values are by far greater than 1, and are larger for raw materials such as fibers or polymers than for semifinished products such as fiber-reinforced composites. The increasing economic and environmental costs of this excessive direct or indirect use of materials trigger a number of strategies to reduce both resource consumption and waste generation.

Synthetic polymers represent a mere 4% of crude oil applications, and their composites are therefore based on nonrenewable resources. As indicated in Table 2, the lifetime of various applications for polymer composites ranges from a few years in the case of consumer goods, up to over 50 years, particularly in the building sector. In the competition with alternative low-weight materials with a clearer environmental strategy, not to say aluminum, life extension of nonrenewable polymer composites has become a major issue. The following highlights the reasons for this need, and indicates routes towards increased durability of the resources used to manufacture polymer composites.

### 2.33.1.2 Loop Closing of Composite Materials

Besides dematerialization, loop closing of resources is one of the key criteria towards sustainability. The extent to which a resource

loop is closed depends on the respective durability of the material and the corresponding resource, and is attainable through: (i) increased durability, (ii) increased use of renewable resources, and (iii) increased reuse of products and recycling of materials (Lundquist *et al.*, 1999a, 1999b).

Which route, or combination thereof, would provide the optimal solution in terms of sustainability, that is, for economic, technological, and environmental criteria, is not always evident. It often requires trade-offs, as we have learned from examples in recent years. Increasing the durability of a product could have adverse effects on developing novel products with lowered environmental burden: a typical example is that of cars. Increasing the use of renewable resources might imply increasing the use of hazardous substances for cultivation and processing, and would considerably impede the number of times the material can be recycled. Finally, increasing the recycling level of materials goes along with well-recognized drawbacks, including the drop in quality of used materials, which imply, when recycling, an overdesign to compensate for such a drop, with a clear economic implication.

### 2.33.1.3 The Criteria and Analyses of Durability

Durability is a key concept for the development of polymer composites, since uncertainties about long-term behavior of these materials often translate into conservative design. There is, however, no general definition of durability, since it obviously depends on the application to be used in an unknown future. Typically, it is in the case of aircraft structures, 12 000 h in a supersonic regime, under cyclic loads and temperatures up to 175 °C (Arnold-McKenna and McKenna, 1993) or, in the case of composite hulls for submersible intended for 6000 m depth, several years with pressure cycles beyond 600 bars, in a marine environment (Davies *et al.*, 1996). Similarly, flexible piping systems for offshore applications are expected to resist to operating pressures of 690 bars, temperatures of 145 °C, depths exceeding 1500 m, and extremely aggressive production fluids (Quigley *et al.*, 1998).

#### 2.33.1.3.1 Limiting factors to composite durability

Although an exhaustive list of factors contributing to reaching the end of the life of a

composite part is not accessible, one may distinguish the following three main causes:

(i) *Aging and degradation of the material constituents.* These phenomena which lead, depending on the field of application, to structural or functional failure of the composite part, are described in Section 2.33.2. These typically include premature failure of the product due for instance to excessive levels of internal stresses.

(ii) *Improper design and processing cycle.* This situation involves primarily drastic limitations to part re-use as well as material recycling resulting from the inherent complexity of the constituent assembly, and therefore difficulties in disassembly.

(iii) *Product obsolescence.* The third limiting factor to composite durability finds its causes in the rapid technological progress, mostly within the area of computer goods and telecommunications. It further results from changing consumer patterns, where a typical example is that of sports goods which use more and more polymer-based composite materials. This topic is beyond the scope of this chapter, and the reader is referred to the works of, e.g., Giarini and Stahel (1993), Lemer (1996), or Kimura *et al.* (1998).

#### 2.33.1.3.2 Durability analyses of polymer composites

Three main axes for durability analysis have been identified to analyze and predict the long-term evolution of polymer composites under a complex interplay of mechanical, thermal, and environmental factors. These were reviewed by Cardon (1996b), and extensively developed in several publications devoted to this topic (Cardon and Verchery, 1991; Wetherhold, 1994; Cardon *et al.*, 1996; Cardon, 1996a; Reifsnider *et al.*, 1998).

(i) The *reduced time* approach promoted by Schapery (1969, 1996) allows extrapolations of long-term response from short-term tests, using time–temperature, time–aging time, and other time–moisture superposition principles. This approach stems from a thermodynamic formulation of nonlinear viscoelastic and viscoplastic constitutive equations. It is used for instance to model structural recovery and moisture effects in high-performance composites (Brinson, 1991; Brinson and Gates, 1995).

(ii) The *damage mechanics* approaches of Talreja, Allen, Ladeveze, Tamusz, and Nairn, to cite only a few (Talreja, 1985, 1994), relate the composite stiffness reduction to the progressive development of microdefects such as

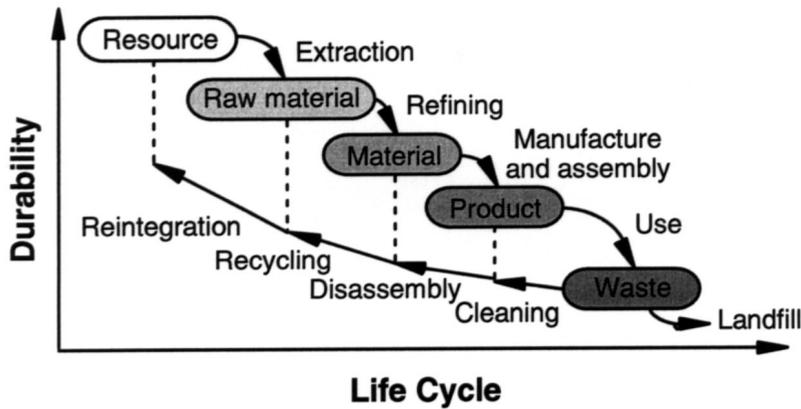


Figure 2 Schematics of the drop in durability of materials at each life cycle step.

matrix transverse cracking in laminates. The literature is rich in works devoted to the modeling of these ubiquitous phenomena, and most refer to the notion of internal variables, in the thermodynamic sense, to describe the state of damage.

(iii) The *critical element* approach introduced by Reifsnider and co-workers (Reifsnider and Stinchcomb, 1986; Reifsnider, 1991; Reifsnider *et al.*, 1996), where the failure of the composite is controlled by that of a critical representative volume affected by a defined failure mode, identified from laboratory tests. This approach has been implemented into the MRLife computer code to predict the remaining strength and life of polymer composites.

#### 2.33.1.3.3 The life cycle approach to composite durability

Figure 2 sketches the influence of the life cycle steps on the durability of a material, such as any of the constituents of a polymer composite. It is evident that the durability of the material drops at each individual step. The three main factors leading to such a drop were introduced in the previous section. There is widespread agreement that insufficient knowledge about aging and degradation mechanisms, and particularly about the coupling between phenomena, is a central concern in durability prediction of polymer composites. Improved processing cycles and understanding of the long-term behavior of this class of materials would translate into less overdesign, minimized maintenance efforts, and extended lifetime. Besides, improvements in design, material selection, and assembly practices would benefit from incentives to recover individual parts in complex assemblies at all stages of the life cycle of the composite.

With this approach in mind, the objective of life cycle engineering may be seen as maintaining the durability of the constituent materials shown in Figure 2 to the highest possible level during the whole life cycle.

#### 2.33.1.3.4 Priorities in life cycle engineering

Life cycle engineering puts priority on prevention principles, which should be activated in the early stages of the design process (Luttrop and Züst, 1998). As shown in Figure 3, the top priority in terms of resource sustainability is to substitute a service to a product, which has been termed dematerialization (Wernick *et al.*, 1996). Examples of dematerialization range from lowering weight of containers or cars, for which low-weight composite structures play a central role, to substitution of paper by electronic formats, although the influence of the latter on dematerialization is still unclear. Similarly, high priority is to be given to all life extension options, including maintenance, repair, and reuse, providing that no alternative product or service with less impact on the environment can be used.

Recycling, including mechanical recycling and chemical recycling, brings the durability of the constituents back to a higher value. It is nevertheless a lower priority option, particularly when it requires larger material and energy inputs compared to the preceding life extension alternatives. Finally, feedstock recycling, where the polymer constituent is recovered back into fuel-like products, and energy recovery, are to be considered as low-value alternatives. It should, however, be made clear at this point that which recycling or recovery alternative, or combination thereof, will provide the optimal environmental benefit has to be evaluated. This topic will be addressed in Section 2.33.5.



**Figure 3** Priorities in life cycle engineering.

According to this hierarchy, incineration without energy recovery and dumping into landfill are not considered as viable alternatives to resource management, as these bring the durability of the resource to zero.

### 2.33.2 THE LIFE CYCLE OF POLYMER COMPOSITES

#### 2.33.2.1 The Nature of Material Constituents

The following summarizes the features of the constituents of polymer composites relevant to the influence of the life cycle on their durability.

##### 2.33.2.1.1 Polymer matrices

Polymers are organic materials. As such, they tend to degrade under thermomechanical loads, and degrade even more in the presence of oxygen, moisture, and radiation such as ultraviolet, to which they are generally poor barriers (Brown, 1993; Clough *et al.*, 1996). Biodegradation of polymers is a further topic related to the life cycle of organic materials, which nonetheless is beyond the scope of the present work, and the reader is referred to the compilations of Lenz (1993) and Albertsson and Huang (1995). Polymers are also macromolecular assemblies, characterized by unique time-dependent properties, resulting in a variety of so-called viscoelastic phenomena including creep and lack of dimensional stability (Aklonis *et al.*, 1972; Ferry, 1980; Christensen, 1982). Moreover, polymers are seldom in thermodynamic equilibrium. Crystalline structures frozen-in during the cooling stage of a processing cycle may evolve towards higher crystallinity, particularly in the presence of plastification agents such as moisture. Besides, the slow recovery back

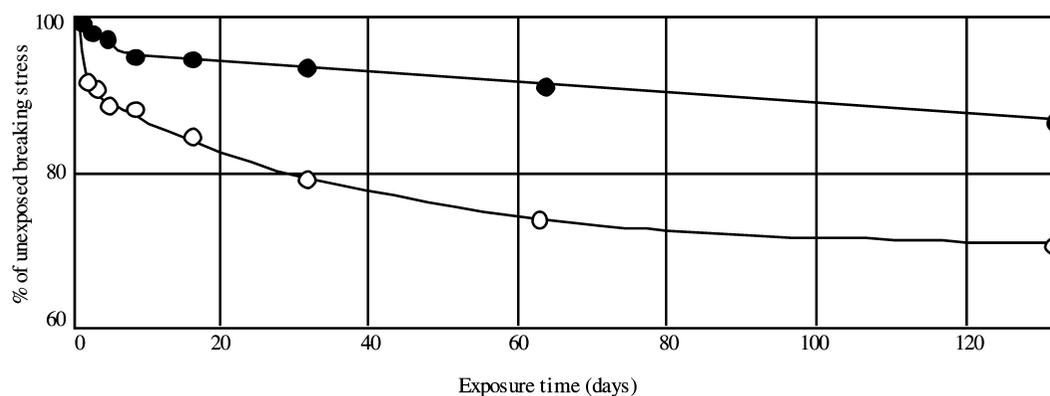
towards equilibrium of amorphous glassy polymers translates into additional time-dependent effects termed physical aging (Struik, 1978; Hutchinson, 1995). These three key characteristics of polymer materials with associated phenomenology are summarized in Table 3.

##### 2.33.2.1.2 Fiber reinforcements

Most of the fibers used to reinforce polymer matrices, including glass, boron, and carbon, are brittle, their mechanical strength being limited by surface flaws. Fiber attrition in viscous polymer melts during extrusion compounding, and fiber/fiber wear, particularly in textile technology, are typical concerns. As brittle materials, the strength of fiber filaments is defect-controlled and as such, is dependent on the length of the fiber. Probability distributions accounting for surface flaw dependent strength have traditionally been associated with the Weibull function (Weibull, 1951). It was used extensively to derive the strength of carbon and glass fibers tested at various gauge lengths (Asloun *et al.*, 1989; Padgett *et al.*, 1995; Dibenedetto *et al.*, 1997; Tagawa and Miyata, 1997; Wang and Xia, 1997), or indirectly, using single-fiber composite (Curtin, 1994; Goda *et al.*, 1995) or acoustic emission (Okoroafor and Hill, 1995; Clough and McDonough, 1996). Besides being brittle, glass fibers are also susceptible to hydrolysis, which affects their mechanical strength (Thomas, 1960; Aslanova, 1985; Bansal and Doremus, 1986; German and Yannacopoulos, 1997; Vauthier *et al.*, 1998), as shown, for instance, in Figure 4. Similarly aramid fibers are sensitive to moisture with reported creep rate increase (Dillard *et al.*, 1991). Particular mention should finally be made of the case of lignocellulosic fibers which, by contrast with synthetic fibers, are

**Table 3** Factors contributing to aging and degradation of polymer matrices.

Nature of polymers	Aging and degradation factors	Phenomenology
(i) Organic matter	<ul style="list-style-type: none"> <li>● Temperature (pyrolysis)</li> <li>● O<sub>2</sub> (oxidation)</li> <li>● Radiation, incl. UV (oxidation)</li> <li>● Solvents, incl. H<sub>2</sub>O (solvolysis)</li> <li>● Biodegradation</li> <li>● Mechanical load; melt state</li> </ul>	<ul style="list-style-type: none"> <li>● Molecular scission</li> <li>● Yellowing, embrittlement</li> <li>● Discoloration, embrittlement</li> <li>● Plastification</li> <li>● Enzymatic/bacterial action</li> <li>● Extensional degradation; Shear and viscous heating</li> </ul>
(ii) Macromolecular organization	<ul style="list-style-type: none"> <li>● Sorption of gases and liquids</li> <li>● Mechanical load; solid state</li> <li>● Time, temperature, stress</li> </ul>	<ul style="list-style-type: none"> <li>● Swelling and drop in <math>T_g</math></li> <li>● Yield, fatigue failure</li> <li>● Viscoelasticity (creep, lack of dimensional stability)</li> </ul>
(iii) Nonequilibrium state	<ul style="list-style-type: none"> <li>● Time and temperature</li> <li>● Time, temperature, stress</li> </ul>	<ul style="list-style-type: none"> <li>● Cross-linking of network; Recrystallization</li> <li>● Structural recovery and physical aging</li> </ul>



**Figure 4** Variation of percentage tensile strength of pristine glass with exposure time at 0 (black dots) and 100% (white dots) relative humidities (reproduced by permission of the Society of Glass Technology from *Phys. Chem. Glasses*, 1960, 1, 4–18).

particularly moisture- and temperature-sensitive (Bledzki *et al.*, 1998).

### 2.33.2.1.3 Interface

There is no need to remind the reader about the key role played by filler–matrix interfaces and ply–ply interfaces on composite performance, through their stress transfer capability, as detailed in several publications (Ishida, 1990; Gorbatkina, 1992; Akovali, 1993; Kim and Mai, 1998). Only few studies, however, have specifically addressed the relation between the type of interactions, the internal stress state, and the degradation processes germane to the interfacial region (e.g., Morii *et al.*, 1991; Meyer *et al.*, 1994; Bradley and Grant, 1995; Eriksson *et al.*, 1996a; Tsotsis and Lee, 1998), by contrast with ceramic matrix composites or metal–oxide interfaces.

### 2.33.2.2 Brief Review of Aging and Degradation Phenomena

Process-induced degradation (i.e., high temperature) and service-induced degradation (i.e., low temperature) are treated in separate sections in the following, although several features are common to both phenomena. As was illustrated in Figure 2, it is also important to stress that the latter phenomena are greatly influenced by the former, which becomes obvious in the case of closed-loop recycling.

#### 2.33.2.2.1 Process-induced degradation

Matrix degradation and fiber attrition are the two main causes responsible for degradation of polymer composites during a processing operation. On the one hand, all commercial polymer matrices are protected with antioxi-

dant additives, as the dominant polymer degradation mechanism is the thermally activated oxidative degradation (Zweifel, 1998), in which the action of oxygen at high temperatures leads, depending on the polymer type, to a decrease of molecular weight and/or cross-linking. Viscous or adiabatic heating of the polymer melt, due to the combination of intense shear rates and low thermal conductivity, further contribute to such degradation phenomena. Other chemical degradation processes involve thermal degradation and solvolysis reactions such as hydrolysis, which is a main concern in the processing of natural fiber composites, as reviewed by Bledzki *et al.* (1998) in the case of thermoplastics reinforced with wood fillers. Besides, mechanical degradation of the polymer may occur in particularly severe elongational fields which provoke unfolding and scission of the macromolecules.

On the other hand, fiber attrition is a central issue in processes involving shear flow of highly viscous polymers, typical of thermoplastic extrusion compounding and molding techniques. It is the consequence of the limited bending strength of the fibers, as was studied for example by Mittal *et al.* (1988), Wolf (1994), Ramani *et al.* (1995), and Eriksson *et al.* (1996b), as a result of multiple reprocessing.

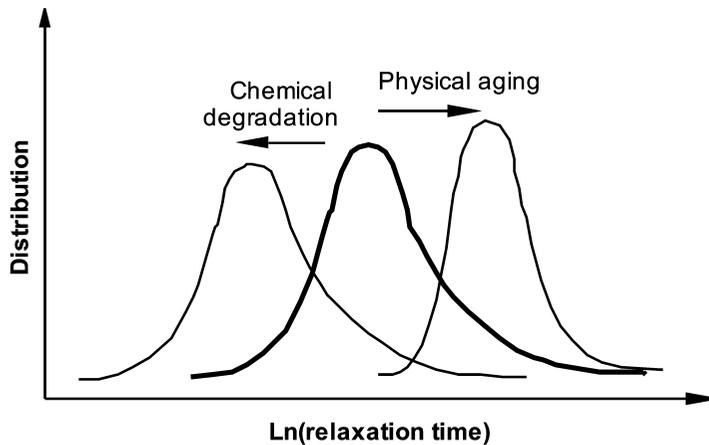
#### 2.33.2.2.2 Service-induced degradation

Similarly to the high-temperature regime relevant to most processing operations, thermo-oxidation is a key feature responsible for service-induced degradation of polymer composites. Seferis and co-workers have investigated the degradation processes of this class of materials through weight loss measurements taking into account their inherent anisotropy and heterogeneity (Hayes and Seferis, 1996; Salin and Seferis, 1996). Tsotsis (1995) and Tsotsis and Lee (1998) report comprehensive analyses of the thermo-oxidative degradation of carbon-fiber reinforced epoxy composites, which demonstrate the respective importance of matrix and interface degradation, matrix toughness, ply interaction, and edge effects. Correa *et al.* (1996) found that the thermal resistance of aramid fiber reinforced composites was greater than that of carbon fiber reinforced composites or the pure matrix polymer, due to improved interfacial interactions. Furthermore, environmental aging combines the action of oxygen in the air, light, moisture and temperature, and, possibly, mechanical loads. The action of oxygen appears to be the dominant factor in the evolution of the mechanical response of both fiber-reinforced

thermosetting and thermoplastic composites during long-term environmental exposure, as concluded by Parvatareddy *et al.* (1995). Additional information can be found in the review of Tant *et al.* (1995), devoted to the high temperature properties and applications of polymers and polymer composites.

Sorption of small penetrants by the polymer matrix, particularly water, often plasticize or swell and induce microcracks in the polymer. It may also damage the interface through osmotic pressure effects and eventually degrade the fiber reinforcement, for instance, through hydrolysis of glass. Mensitieri *et al.* (1995) and Weitsman (1998) have reviewed the salient features of moisture and solvent sorption in polymer matrices, particularly epoxy, polyester, and PEEK. Chemical resistance of glass fibers is well documented (Bansal and Doremus, 1986) and is largely dependent on their composition. For instance, Ghosh and Bose (1995) investigated the higher hygrothermal resistance of N-glass fibers compared to E-glass fibers, in spite of the lower mechanical strength of the former. Schutte (1994) reviewed the various characteristics of moisture degradation of polymer composites. Further information is found in the works of Selzer and Friedrich (1995) and Vauthier *et al.* (1998), as well as in the compilation of Chiang and McKenna (1996), and in the studies of the effects of non-Fickian water diffusion in fiber-reinforced composites of Cai and Weitsman (1994), to cite only a few. Due to the considerable development of this class of materials for structural marine applications, the specific role of seawater has also been extensively studied, for instance, by Bradley and Grant (1995) and Davies *et al.* (1998).

Coupling and sizing agents were correlatively developed to improve interfacial adhesion and durability, as studied by Fraser *et al.* (1975). The influence of the chemistry and morphology of coupling agents on glass fibers on the durability of the interfacial region was reviewed by Schutte (1994). It was analyzed by McKnight and Gillespie (1997) in the case of glass fibers, by Helmer *et al.* (1995) in the case of carbon fibers, and by Bledzki *et al.* (1998) and Gauthier *et al.* (1998) in the case of natural fillers. Alternative surface treatments have been developed, such as electrochemical, ozone, and cryogenic fiber modifications studied by Rashkovan and Korabelnikov (1997), using the single-fiber composite adhesion test to determine their efficiency. The relation between the strength of individual filaments and that of the reinforced composite has further motivated a large body of research. Recent works on that topic include studies of Phoenix *et al.* (1997), devoted to statistical analysis of the strength of



**Figure 5** Schematics of the shift of the viscoelastic relaxation time spectrum during aging time.

unidirectional composites, and of Curtin and Takeda (1998) and Shikula (1998).

The issue of biodegradation of composites is beyond the scope of this chapter, but one may cite the work of Gatenholm *et al.* (1992) and Gatenholm and Mathiasson (1994) who have for instance processed biocomposites based on cellulose and biodegradable polymers, particularly bacteria-produced polyester copolymers (polyhydroxybutyrate-hydroxyvalerate, PHB-HV) reinforced with wood cellulose. An excellent dispersion of cellulose fibers was achieved in the PHB matrix compared with such synthetic matrices as polystyrene or polypropylene.

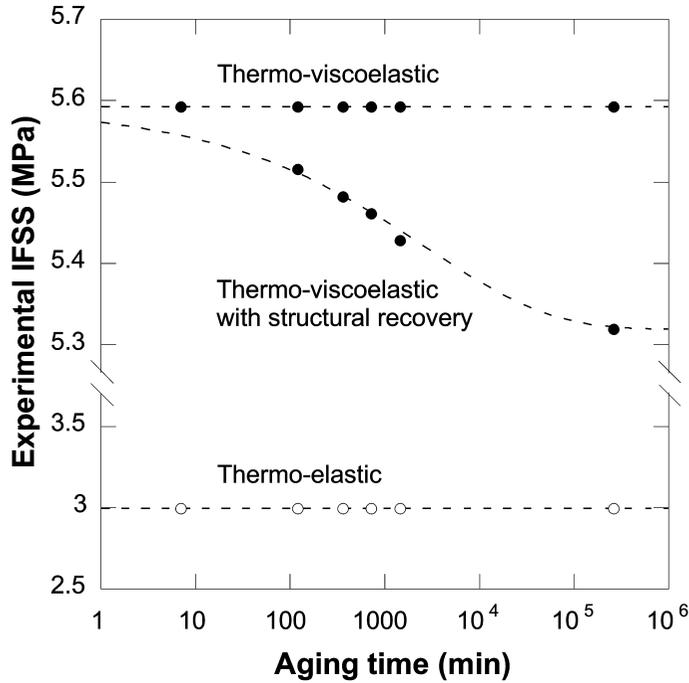
#### 2.33.2.2.3 Viscoelasticity and aging during service

The time dependence of polymer composites has received increasing attention in the 1990s (e.g., Tuttle *et al.*, 1995) (see Chapter 2.10, this volume). Particularly, their nonlinear viscoelastic behavior has been modeled based on Schapery's hereditary integral (Schapery, 1969, 1996), whereas nonlinear viscoplastic effects were treated using for instance Zapas and Crissman (1984) derivations, both constitutive formulations being implemented in classical lamination theory to characterize the response of laminated composites. Viscoelasticity is described by a relaxation spectrum which is likely to evolve throughout the life of the composite, as a result of the various phenomena described above, similarly to what is depicted in Figure 5.

Upon cooling from above the glass transition temperature to below it, which is the case of most processing operations, amorphous polymers depart from thermodynamic equilibrium. The slow evolution of the nonequilibrium state of the viscoelastic material,

characterized by a distribution of relaxation times, back towards equilibrium, has been termed structural recovery and extensively studied in the case of polymers since the late 1950s (Kovacs, 1958, 1963). The consequences of the recovery phenomenon can be found in the evolution of mechanical, electrical (Li and Unsworth, 1994), and optical properties, and, in general, in any property which is a function of molecular mobility. Practically, an increase in the Young's modulus and yield stress or a decrease in the creep rate have been reported as a result of structural recovery. Such time-dependent evolution of properties came to be coined physical aging and was extensively studied by Struik (1978) in the case of amorphous and semicrystalline polymers and other glassy materials.

To our knowledge, Kong (1981) was the first to report investigations about the physical aging of polymer composites, with studies of the long-term behavior of epoxy/carbon laminates. In the 1990s, significant efforts were devoted to in-depth analyses of the phenomena, in a large variety of thermoset and thermoplastic-reinforced materials (e.g., Ma *et al.*, 1990; Haidar and Vidal, 1996; Maddox and Gillham, 1997). Modeling of the evolution of the viscoelastic behavior of these materials was proposed by Sullivan (1990) and Sullivan *et al.* (1993) using an effective time theory, which provided good agreement with a large variety of composite systems and, more recently, by Leterrier and co-workers, accounting for internal stresses (Wyser, 1997; Leterrier *et al.*, 1999). Interestingly, Armistead and Snow (1995) found no evidence of aging upon adhesion properties in model composites, besides the effects of internal stresses. This result finds additional support in the studies of Mendels *et al.* (1999a, 1999b). These authors demonstrate that change in adhesion is entirely attributed to the change in the



**Figure 6** Evolution of the isochronous interfacial shear strength between a glass fiber and an epoxy matrix after aging at  $T_g - 5^\circ\text{C}$ . Three different models are compared, as indicated on the graph. The most accurate model couples the thermoviscoelastic relaxation of internal stresses to the structural recovery of the polymer matrix (after Mendels *et al.*, 1999b).

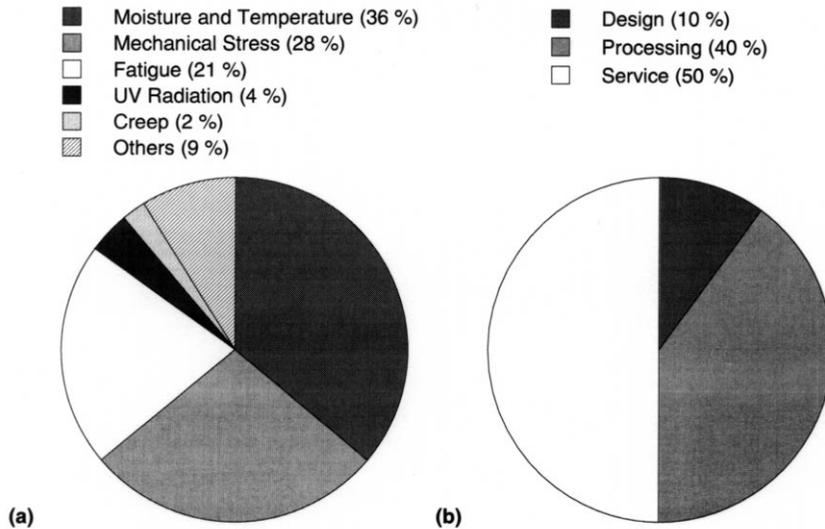
internal stress state resulting from the aging process, as shown in Figure 6 in the case of a glass fiber–epoxy interface, aged below the glass transition temperature of the polymer matrix.

Several authors have refined the modeling efforts by combining effective time theories together with classical laminate theory, including Brinson, Gates, and co-workers (Brinson, 1991; Brinson and Gates, 1995; Bradshaw and Brinson, 1997a, 1997b; Gates *et al.*, 1997; Monaghan *et al.*, 1994; Veazie and Gates, 1997) and Dillard and co-workers (Wang *et al.*, 1995; Parvatareddy *et al.*, 1995, 1998; Pasricha *et al.*, 1997). The latter researchers have also accounted for oxidative degradation processes in adhesive joints. Similarly, Mijovic (1985) had examined the coupling between physical and chemical aging in epoxy/carbon composites, and numerical analyses were recently performed by Huang (1998). A summary of the theoretical developments relevant to the above-mentioned phenomena can be found in the work of Chow (1996).

It is evident that the numerous degradation and aging processes described above, with their own timescales, all act together in complex interplay. This remark calls for a need to analyze coupling effects between these different factors.

#### 2.33.2.2.4 Coupling effects in durability analysis

According to a survey made after several years of expertise on damage composite parts by the French Technical Center for the Mechanical Engineering Industries (CETIM), 41% of failures in composite materials during service that were not attributed to manufacturing defects result from coupled processes. Figure 7 summarizes the various causes for failure, as reviewed by Perreux (1999) from a survey of the French Association for Composite Materials (AMAC). By definition, coupling of phenomena occurs when the overall composite aging cannot be determined from the sum of individual processes resulting from the various aging mechanisms taken separately. A typical coupling situation arises when a structure degraded under an oxidative atmosphere is simultaneously loaded in fatigue: the mechanical load induces further damage in the material, which, in turn, facilitates the diffusion of oxygen, hence, accelerates the degradation. Coupled phenomena systematically accelerate damage of the composite material, and their analysis requires investigation of the characteristic timescales of the various aging factors acting altogether. It should be pointed out that the effect of temperature, at the exception



**Figure 7** Statistics of composite failure, related to environmental causes (a) and life cycle causes (b) (after Perreux, 1999).

of any change in the material state such as additional cross-linking for example, is to accelerate the aging processes, and, as such, is not considered as a factor of coupling. Nevertheless, the presence of thermal transitions in polymers, together with the multiplicity of processes with different activation energies, render accurate analysis of the acceleration effect of temperature very difficult. A comprehensive analysis of coupled phenomena appears to be presently out of reach, and much research efforts are still needed. As an alternative, several protective measures are being developed, which are summarized in the following.

### 2.33.2.3 Health Monitoring and Protective Measures

Besides the theoretical analyses of the durability of polymer composites, efforts are directed towards health monitoring and protective measures. The former involve embedded health sensors and self-monitoring of the composite, otherwise termed “intrinsically smart materials,” through the continuous measurement of electrical resistance which is a function of structural damage, as reviewed by Chung (1998). According to Kranbuehl *et al.* (1996), embedded devices not only offer the capability to allow *in situ* measurements, but are also sound alternatives to aging models, which lack reliability as they should predict an uncertain future. In that sense, health sensors keep predictions on track. Recent developments in this direction include sophisticated neural-net-

work based training introduced by Luo and Hanagud (1997) for real-time flaw detection. A variety of advanced structural health monitoring techniques for composites have been reported. These include the use of active carbon tows (Tamiatto *et al.*, 1998), piezoelectric transducers developed by Moulin *et al.* (1997) and Lichtenwalner *et al.* (1997), and wafer thin microsensors used initially to characterize *in situ* the processing state of polymers (Kranbuehl *et al.*, 1996).

Protection against aging and degradation of polymer composites has traditionally been associated on the one hand with protection of the composite constituents, and, on the other, with the use of protective coatings. The former deals mainly with stabilization of the polymer matrix and the development of tougher fibers, including specific sizing agents to protect the fiber reinforcement. The latter are essentially paints, which, as will be addressed in Section 2.33.4, may be detrimental to the quality of the re-ground material. Hard coatings find considerable interest in tribological applications. They are also used as barrier layers to protect carbon-carbon composites from oxidation under extreme temperatures. Similarly, although to a far lesser extent, oxygen and moisture barrier coatings have been employed to protect polymer composites. To prevent thermo-oxidative degradation, protective coatings resistant to high-temperature and based on vapor deposition techniques have been successfully developed and analyzed by Harding *et al.* (1994) and Miller and Gulino (1994). According to Wyser (1997) and Wyser *et al.* (in press), such thin coatings might further present the

advantage not to limit the recycling potential of the composite.

### 2.33.3 LIFE CYCLE ENGINEERING IN PRODUCT DEVELOPMENT

#### 2.33.3.1 Ecoefficiency and Product Development

Ecoefficiency is, simply put, about producing more with less resources and less pollution, and for more insight, the reader is referred to work of Fiksel (1994) and to the publications of the World Business Council on Sustainable Development (WBCSD, 1995). Life cycle design tools allow the linking of traditional design practices with environmental issues by showing what the environmental issues are and the priorities that need to be addressed. A considerable amount of computer-aided tools are available to reduce the environmental impact of a product, “from cradle to grave,” some of which were compared by Hertwich *et al.* (1997). These tools encompass design for recycling, design for disassembly, design for remanufacture, or design for energy efficiency, and obviously make large use of life cycle assessment methods. They also consider waste minimization, including hazardous waste, and compliance with regulations and standards. Initial efforts were mostly end-of-pipe approaches to help designers avoiding waste and toxic substances. By contrast, in recent years, activities orient more and more towards optimizing the product within sustainable boundaries (White, 1994).

#### 2.33.3.2 The Role of Design in the Life Cycle of Composites

The development of integrated components such as composite parts in light of the life cycle engineering concept should consider the various topics discussed in the preceding sections, particularly issues of material reduction and life extension of products. This section emphasizes the importance of accounting for composite durability and reliability in design strategies. Examples of existing design methodologies such as design for disassembly and design for recycling and products and processes designed with these issues in mind are given.

##### 2.33.3.2.1 Design for disassembly

Disassembly of multimaterial products into monomaterial constituents is a prerequisite for

product life extension, to ease maintenance and repair operations, and also for material recovery into useful applications, and turns out to be a key challenge in the life cycle design of complex products such as composites. Typical guidelines stress “common sense” issues to ease the disassembly operation, by providing easy access to assembly points and easy identification of the type of material. Using fewer dissimilar materials, and fewer subassemblies, benefits to both material recovery rate by increasing material capture, and recovery economics, by decreasing disassembly time. In this sense, design for disassembly complies with design for assembly practices going for product simplification, which, in turn, is in favor of improved reliability. In the case of plastic products, design guidelines often target metal inserts, clamps, and screws, which should be built to be easily separable, or even avoided and replaced by snap-fit systems. Similarly, Tome *et al.* (1999) propose substituting metallic inserts by local fiber-reinforcement areas. Integration of such functions calls for novel processing approaches to composite manufacture, which will be briefly addressed in a later section.

##### 2.33.3.2.2 Design for recycling

Design for recycling targets the same features as design for disassembly. It addresses more specifically the selection of materials and sets their recycling rate. It further points out the need to form recycled materials into new products. Particularly, fewer dissimilar materials in assemblies, or in subassemblies of products designed for disassembly, will improve the possibilities of material life extension. The German association “Verein Deutscher Ingenieure” (VDI) has developed design for recycling guidelines, classified into three distinct stages of recycling: recycling during production, during use, and after use (Dowie and Simon, 1995; see also the standard VDI2243, VDI, 1993). The “all-PP” (PP, polypropylene) dashboard promoted by automotive tier-suppliers is an innovative concept described by Braunmiller *et al.* (1999) to develop a recycling friendly complex composite product. The structure of the instrument panel comprises a PP foam, sandwiched in between a glass-mat reinforced PP frame (GMT) and a TPO-PP/EPDM decorative foil. This close-to monomaterial solution contrasts with the classical dashboard structure, including a metallic or GMT frame, a polyurethane foam, and an ABS/PVC or similar vinyl foil. Designed for recycling, the PP-based structure does not require costly

separation of the three main layers. Great efforts are nevertheless needed to develop efficient closed-loop recycling of this class of materials, as will be dealt with in Section 2.33.4.

### 2.33.3.3 Reduction of Material Intensity

#### 2.33.3.3.1 Weight reduction

In many instances, ecoefficiency is reached when using lightweight materials such as aluminum and polymer composites. The latter, with unique specific stiffness and strength (ASM, 1987; Tsoumis, 1991), are particularly efficient in environmentally-active applications, such as transportation. An example of this is found in the case of the environmentally-aware design of the Copenhagen S-train, developed in the 1990s by the Danish Railway (DSB) where the reduction of the weight was the main concern. In comparison with the generation of S-trains from 1986, the weight per seat has been reduced by 46%, due to a large extent to the use of light materials.

#### 2.33.3.3.2 Process and material integration

Composite laminates are widely used as facing materials in structural sandwich applications, in which they are bound to a low-density core, such as a foam or a honeycomb material. The benefits of such material integration is obvious, including weight savings, despite main drawbacks related for instance to the repair of the sandwich, and to the recovery of the different constituents. The example of the traditional sandwich structure reveals the key trade-off between increased functional integration which goes along with multimaterial integration, and increased recycling potential which, on the contrary, requires single-material products.

Innovative technologies have emerged to resolve to a certain extent this trade-off in the case of thermoplastic composites. This class of materials include neat and short-fiber reinforced grades developed for injection molding processes, as well as continuous fiber reinforced composites processed by compression molding or autoclave bagging operations. The former possesses high design freedom, but limited stiffness, which is opposite to the latter. Wakeman *et al.* (1999a, 1999b) developed methods for process integration of flexible, semiconsolidated fiber tows with high stiffness into a neat polymer substrate part. Combination of process integration and material integration has proven to be a cost-effective technology for

polymer composite parts (Bourban *et al.*, 1998, 1999), and, from a life cycle perspective, would also be beneficial for material recovery purposes.

### 2.33.3.4 Life Extension of Composite Products

Before considering end-of-life treatments developed to extend the life of material constituents, life extension of composite products should have a high priority in the design process, as was illustrated in Figure 3. This in practice implies fast and cost-effective maintenance and repair operations, based on design for assembly and disassembly approaches.

Specific computer-aided design tools have emerged to incorporate issues of life extension into the traditional development of composites. Russell *et al.* (1998) have, for example, simulated the manufacture of filament-wound composites to provide complete material balance to design engineers. Extensive use is also made of computer-based techniques for stress analysis of composite assemblies including strength and life prediction (Reifsnider *et al.*, 1996), and an example for laminates specifically designed for aircrafts can be found in the study of Madenci *et al.* (1998). In the field of construction engineering, there have been an increasing number of developments where the design of composite structures emphasized durability rather than only mechanical criteria such as strength and stiffness (e.g., studies of Meatto and Pilpel, 1998, Iskander and Hassan, 1998, and Ishai and Lifshitz, 1999). The same applies for marine applications, where composite technology is claimed to offer significant life cycle cost savings thanks to reduced maintenance (Bhasin *et al.*, 1998). However, according to Mouring (1998), design and analysis, fabrication, environmental effects, repair, and joining are still weak points in the further development of composites in this field. In aircraft applications, issues of maintenance and repair of structural composites motivate considerable efforts. Cole (1998) has summarized the main achievements, resulting from the creation of the Commercial Aircraft Composite Repair Committee in 1991, to establish an international forum to standardize various aspects of operating commercial aircraft with composite components. Along similar lines, several projects to ease maintenance operations with diagnostic techniques have emerged, for instance the scanning laser Doppler vibrometer method of Castellini and Tomasini (1998) or the laser-ultrasonic technique of Monchalin *et al.* (1998) used to inspect advanced aircraft made of composite materials.

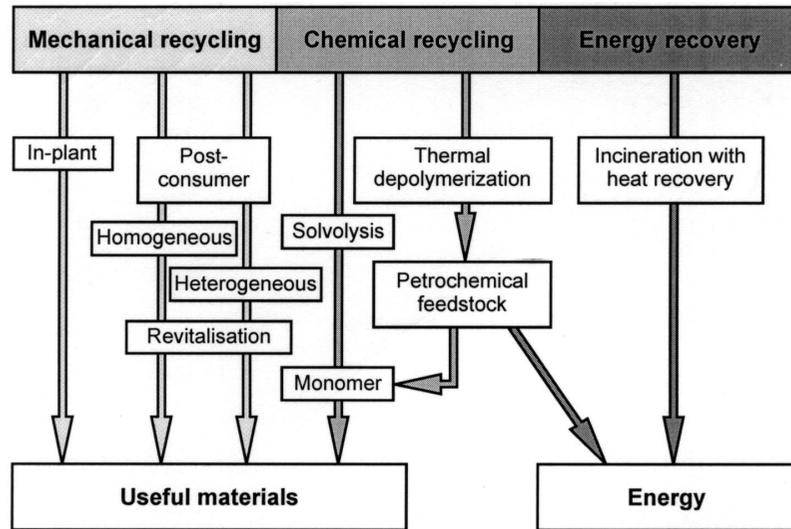


Figure 8 Recycling technologies (adapted from Lundquist *et al.*, 2000).

In the field of repair, Lopata *et al.* (1998) have investigated alternative routes for composites such as traditional thermal cure or electron beam processing, and established the relevance of the latter technique. Polymer composites have also proven to be useful as patches to reinforce damaged metallic aircraft structures, as detailed by Rastogi *et al.* (1998). Reuse and remanufacturing are additional routes to extend the life of products or their components (Guide *et al.*, 1997; Parker, 1997), particularly in the case of environmentally passive applications, as detailed in Section 2.33.5. Material life extension through recycling is treated in the following section.

To be implemented successfully in an industrial context, the technical and design approaches to the life cycle of composites discussed above, or, more generally, resource and waste management issues, should be envisaged in a broad framework of organizational changes, where strategic, economic, and environmental factors strongly interfere. Towards this end, Environmental Management Systems (EMS) have emerged, and have already been implemented in a number of large-scale companies. The topic of EMS goes beyond the scope of this chapter, and the reader is referred to general texts, such as that published by the World Industry Council for the Environment (WICE, 1994).

#### 2.33.4 RECYCLING AND RECOVERY OF POLYMER COMPOSITES

To paraphrase Nadis and McKenzie (1993), one may say “the recycling problem in a word:

composites.” This class of materials, particularly those based on thermosetting matrices, is often considered not to be recyclable, and, consequently, should be phased out in favor of homogeneous materials. Such a statement tends to ignore the overall life cycle environmental impacts as will be addressed in the next section, but nevertheless explains to a certain extent the gradual replacement of thermoset composites by thermoplastic composites, besides other advantages such as reduced process and storage costs. The main sources of polymer composites in the waste stream are from the electric and electronic (E&E) industry, including the consumer market such as household electrical equipment and the automotive industry which has become a clear target in the past few years. The autoshredder residue (ASR) contains, for instance, about one-third of synthetic materials (Disler and Keller, 1997). In all these fields, the waste composites possess interesting economic value for recycling, and current efforts to recover this value are detailed as follows.

Three main recycling techniques are available for polymers and their composites: (i) recovery of materials by chemical processes, (ii) incorporation of regrind during compounding, and (iii) energy recovery through incineration. Figure 8 summarizes the various recycling routes developed for plastics (Ehrig, 1992; Cornell, 1995); the specific processes and limitations relevant for composites are developed in the following. It is obvious that, besides technical requirements, the success of recycling also depends on initial design, logistics of collection, and eventually on the market for the secondary application.

### 2.33.4.1 Chemical Routes to Recycling

Chemical recycling, which includes feedstock recycling, is essentially applied to the polymer fraction, and can be broken down into four classes (Reinink, 1993; Wanjek and Stabel, 1994): (i) solvolysis, (ii) oxidative processes, (iii) pyrolysis and similar thermal decomposition processes, and (iv) reductive processes. Solvolysis is a generic term which includes glycolysis, methanolysis, alcoholysis, ammonolysis, and hydrolysis, as it involves reactions with the corresponding solvents. The solvolysis process is used mainly to depolymerize condensation-type polymers such as PET, PA, PMMA, and PC, plus a few addition-type polymers such as polyurethanes, back into oligomers and original monomers, which, subsequently, can be repolymerized into virgin materials. Addition-type polymers including polyolefins can be treated according to the three other processes. Specific achievements concern for instance recycling of automotive shredder residues, for which Abrams *et al.* (1997) present a catalytic extraction process to produce gas for electricity generation and inert oxides that can be incorporated with construction materials. Since methanolysis or glycolysis of PET has been developed, Rebeiz *et al.* (1993a, 1993b) have studied PET recycling in composites. Similarly, Aslan *et al.* (1997) have reacted products resulting from the glycolysis of PET used in soft drink bottles with mixtures of saturated and unsaturated acids yielding unsaturated polyester suitable as a matrix for fiber-reinforced composites, with toughness improvement. Efforts have been directed by Patel *et al.* (1993) towards recycling of sheet molding compounds (SMC) through solvent extraction, hydrolysis, and pyrolysis. The latter process yields oily organic residues potentially interesting as nonreactive extenders for epoxies and inorganic residues to be used as fillers in a variety of polymer systems. Innovative studies examine reversible cross-linked networks, such as epoxies and unsaturated polyesters, which would be appropriate for recovery purposes (Sastri and Tesoro, 1990; Tesoro and Sastri, 1990). Simon and Kaminsky (1998) have recycled production wastes of different polytetrafluoroethylene (PTFE) compounds containing carbon black, glass fibers, and bronze by pyrolysis in a fluidized-bed reactor, yielding tetrafluoroethylene (TFE) and hexafluoropropene (HFP) monomers for the production of fluoropolymers. The potential and unique benefits of chemical recycling, and promising research directions, have been outlined by Tesoro and Wu (1995).

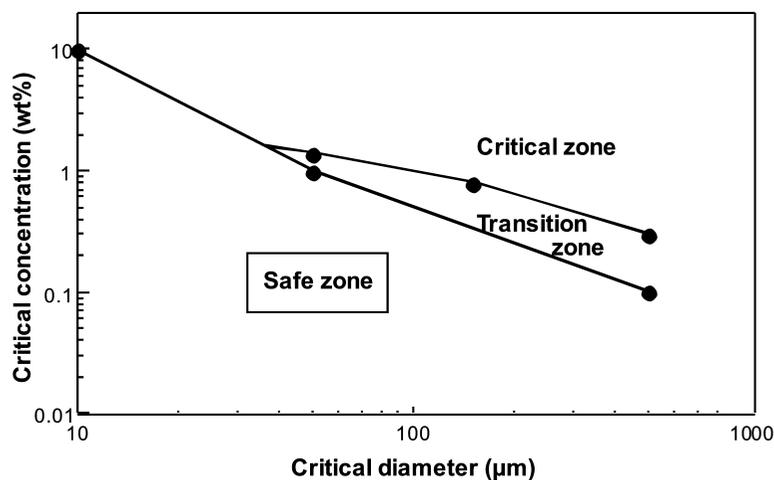
### 2.33.4.2 Mechanical Recycling and Quality Insurance

Mechanical recycling of polymers and polymer-based composites is in constant progress, driven by tight legislation in the field of waste treatment. However, a systematic drop in quality occurs as a result of the reprocessing operation. Quality assessment of the recycled material thus requires thorough analyses of its durability and reliability. Efforts in this direction are reported in the following, in the case of thermoplastic and thermoset matrix composites.

#### 2.33.4.2.1 Thermoplastic composites

Limiting factors to the performance of recycled thermoplastic composites are essentially related to process-induced matrix degradation and fiber attrition, and the subsequent service-induced degradation and aging of the polymer matrix that has undergone several process cycles (see Chapter 2.25, this volume). Additional performance drop could result from contamination by, for example, fragments of cross-linked paint coating or incompatible polymer fractions. As a tool for quality assessment, which is crucial to the market acceptance of recycled materials, modeling efforts have arisen with the aim of predicting the properties of mixtures of virgin and reprocessed fiber-reinforced polymers (e.g., Bernardo *et al.*, 1993, 1996; Throne, 1987). Parametric studies of Bernardo *et al.* (1996) indicate for instance that, for glass-fiber-reinforced thermoplastics, the data on the degradation of fiber lengths and mechanical properties help understanding of the effect of reprocessing on the fiber–matrix interaction. Most of the research and development of recycled thermoplastic composites examine specific cases, as reported in the following.

Recycling of glass-fiber reinforced polyamide developed for a car air intake manifold, radiator end-caps, and similar under-the-bonnet applications has particularly motivated research efforts in recent years. Dzeskiewicz *et al.* (1993) examined the recycling potential of glass fiber reinforced polyamides, and measured a systematic drop in mechanical properties (tensile strength, elongation, and impact) after one and two regrinding and injection molding operations. Eriksson *et al.* (1996a, 1996b) performed an in-depth study of recycling and durability of 30 wt.% short glass fiber reinforced polyamide 66. It was found that fiber length distribution, and not matrix or interfacial thermal degradation, controls the overall short-term performance of the recycled composite. The same



**Figure 9** Critical concentration vs. critical diameter of simulated impurities (glass beads) based on maintained tensile strength of glass fiber reinforced polyamide 66 (reproduced by permission of the Society of Plastic Engineers from *Polym. Eng. Sci.*, 1998, **38**, 749–756).

authors established that fiber attrition dominates during initial compounding and first injection molding, whereas it is less severe during further regrinding and remolding and that, below 50 wt.% regrind, the short-term strength remains within design limits. The specific roles of oxidative degradation (Eriksson *et al.*, 1997a, 1997b), of coolant aging, and of EPDM rubber impurities (Eriksson *et al.*, 1998b) on embrittlement of the composite were identified. A negative influence of the glass fibers on the polyamide oxidative stability was found (Eriksson *et al.*, 1998c). The deterioration rate of recycled composites containing up to 25 wt.% regrind was similar to that of virgin samples during thermal aging but slightly faster during coolant aging (Eriksson *et al.*, 1998a). Finally, critical sizes and concentrations of impurities below which a safe mechanical behavior is achieved were also determined, as shown in Figure 9.

Chu and Sullivan (1996) have established that recycled fiber-reinforced polycarbonate possesses properties as good as or better than a comparable commercial composite. Injection and extrusion compression molding yielded recycled composites with good tensile properties, at the expense of impact strength, whereas the opposite was true for compression molded samples, as a result of corresponding fiber orientation distributions. Recycling studies of polyether-ether-ketone (PEEK) composites reinforced with 10 wt.% and 30 wt.% short carbon fibers by Sarasua and Pouyet (1997) revealed degradation of fibers and matrix during recycling, with subsequent reductions in Young's modulus and strength, as well as impact strength. The recyclability of a polybu-

tylene terephthalate cyclic thermoplastic composite with 58.7 wt.% fibers has been investigated by Steenkamer and Sullivan (1997a) using a grinding, compounding, and injection molding process. The authors found that the recycled composite had similar properties to a commercially available short fiber reinforced thermoplastic composite, with, however, a 25% drop in elongation at break. Czvikovszky and Hargitai (1997) examined the recycling of polypropylene copolymers from automobile bumpers by reinforcing with eight different types of high-strength fibers, using reactive modification (low-energy electron beam) of the fiber-matrix interface. The recycled material could be extruded and injection-molded into fiber-reinforced thermoplastic of enhanced bending strength, increased modulus of elasticity, and acceptable impact strength. Similarly, Wiegiersma *et al.* (1997) used glass fibers to reinforce and improve the impact strength of recycled PET. These various results all support the development of design for recycling reported earlier, such as that of Braunmiller *et al.* (1999).

An alternative to mechanical grinding, which is systematically associated with mechanical recycling, has been promoted by Papaspyrides and co-workers since the late 1970s, using selective dissolution of the polymer fraction, followed by filtration under pressure to recover separately the fibers from the polymer solution (Papaspyrides and Poulakis, 1997; Papaspyrides *et al.*, 1995). The technique allows removal of contaminants and degraded species such as cross-linked molecules. The authors also indicate that it offers the advantage of yielding controlled amounts of residual polymer

**Table 4** Mechanical properties of composites containing recycled SMC fractions.

<i>Composite</i>	<i>Modulus (GPa)</i>	<i>Strength (MPa)</i>	<i>Elongation at break (%)</i>
Reference SMC (25% glass fibers) <sup>a</sup>	14	86	0.9
Reference BMC <sup>b</sup>	13.1	27.9	0.44
BMC + 20% SMC coarse regrind <sup>b</sup>	9.2	14.5	0.34
BMC + 20% SMC fine regrind <sup>b</sup>	10.2	16.1	0.14
PP + 9% chopped glass <sup>b</sup>	2.00	37.9	3.45
PP + 30% SMC coarse regrind <sup>b</sup>	2.20	21.0	2.34
PP + 30% SMC fine regrind <sup>b</sup>	2.07	20.9	2.47
Epoxy + 20% (GF and CaCO <sub>3</sub> from SMC) <sup>c</sup>	–	35.0	3.0

Sources: <sup>a</sup> Dana (1991); <sup>b</sup> Farrissey (1992); <sup>c</sup> Patel *et al.* (1993).

attached to the recovered fibers (Poulakis *et al.*, 1997a). This polymer coating acts as a compatibilizer, thus improving dispersion in case of reprocessing into virgin resins, such as polypropylene. It leads to the formation of a unique interphase, that was found to be beneficial for modulus and strength of the composite, but detrimental to impact strength (Poulakis and Papispyrides, 1997; Poulakis *et al.*, 1997b). Ramakrishna *et al.* (1997) have compared the selective dissolution technique with a comminution technique in the case of a carbon fiber reinforced PEEK, the latter eventually found to be the most efficient. Theoretical treatment of the dissolution rates for highly filled polymers was recently developed by Cao *et al.* (1998).

#### 2.33.4.2.2 Thermoset composites

A prerequisite to reusing thermoset resins and their composites as regrind is to reduce by shredding and grinding the size of the parts into flakes or powder fractions with controlled sizes (Farrissey, 1992) (see Chapter 2.19, this volume). The techniques developed for this are capable of generating a large variety of regrind fractions containing defined fiber length distributions, as indicated by Kelderman (1995). In the 1980s, the regrind was mostly used as filler, either in uncured thermoset resins or in virgin thermoplastics. It was also used with adhesive binders, where a large fraction of regrind is bound together with a small amount of adhesive. Later on, the potential of the regrind fraction as reinforcement has been explored. Major efforts have been directed to recycling sheet molding compounds (SMC) and bulk molding compounds (BMC), which represent ca. 50% of all composites. One may cite the SMC Automotive Alliance aiming at developing commercial processes to convert composite scrap into new automotive applications. The

best SMC recycling approach was claimed by Jost (1995) to be grinding waste composite into filler and fiber fractions. Developing markets include construction, friction materials, putty, and reinforced thermoplastic and other thermoset industries. Current research programs devoted to SMC recycling stress the need for quality insurance of the recycled materials to avoid downcycling. To this end, Bledzki *et al.* (1995) proposed an experimental design plan to analyze the mechanical performance of such materials. The ERCOM composite recycling organization was founded in 1991, targeting the suppliers of the automotive and electrotechnical fields. The program is based on the principle of recycling by grinding used materials down to fiber-rich fractions suitable for mixing with new SMC materials as fillers and reinforcements; the fact that the resin does not melt proved to be an advantage in terms of compatibility (Kelderman, 1995; Schaefer, 1995, 1997). Additional information about SMC recycling can be found in Chapter 2.22, this volume. Table 4 reports data extracted from the literature relating to the mechanical performance of SMC, BMC, and composites containing SMC regrind fractions.

Besides the SMC recycling activities, dedicated projects were developed for specific thermoset composite recycling, such as glass-fiber reinforced polyester/PUR sandwich structures developed for building applications, for which Mlecnik (1997) emphasized the need for design for reuse tools. An Internordic program entitled "Recycling of Thermoset Composites" was launched by the Swedish Institute for Composites (NUTEC-SICOMP), with several projects related for example to the recycling of boats (Pettersson and Nilsson, 1997). Another example was reported by Vasut *et al.* (1999) who have studied the recycling of automotive wastes, such as rubber-thermoplastic reinforced composites, into noise abatement structures along highways.

### 2.33.4.2.3 Fiber reinforcements

This section mainly concerns the recycling of general-purpose glass into fibers to be used as reinforcements in polymer composites. Studies have shown that the performance of unsaturated polyester structural composites reinforced with A-glass (primarily composed of soda lime silicate) recycled fibers is comparable to that of reference composites reinforced with traditional E-glass, providing the A-glass fiber fraction is increased to offset their lower mechanical strength compared with the E-glass fibers (Steenkamer and Sullivan, 1997b). Kennerley *et al.* (1998) propose using a fluidized-bed process to recover glass fibers from SMC composites scrap. Glass fibers recovered at 450°C using this process, whose strength is reduced to about half that of virgin fibers, have been used as partial and full replacement for virgin fibers in a dough molding compound (DMC). A drop in mechanical strength was noticed at recycled fiber fractions above 50%, whereas the flexural and Young's moduli were found to remain unaffected.

### 2.33.4.3 Incineration and Energy Recovery Routes

Incineration significantly reduces the volume of waste materials and, as such, has been promoted as an alternative to the prevalent method of disposal into landfills, nowadays prohibitive due to increased cost, negative public opinion, and legislation. Clearly, these two waste management routes lead to a total loss of the material value, and are further not free from environmental impacts. By contrast, when combined with energy recovery, incineration of waste finds increasing support as a viable recycling method. For more information on the energy recovery of plastics, the reader is referred to the documents published by Mark and Vehlow (1998) under the auspices of the APME.

Most of the efforts devoted to energy recovery of polymer composites can be associated with studies on automotive shredder residues (ASRs). Since 1990, the SMC Automotive Alliance, with 30 suppliers of the auto industry, promotes the combination of pyrolysis processes with mechanical recycling as the most realistic mid-term disposal options for ASR (see, for instance, *Automotive Engineering*, 1994). Unser *et al.* (1996) have explored recovery methods for composites, which convert the polymer matrix to lower chain hydrocarbons and fuel gas leaving behind fibers, used with success in bulk molding compounds panels,

reinforced concrete, and compression molded panels. The suitability of the pyrolysis process for recycling SMC has been investigated as an alternative to the mechanical recycling route by Demarco *et al.* (1997). Studies have shown that temperatures in the range of 400–500°C are the most suitable for recycling SMC by pyrolysis. In the case of a glass fiber reinforced orthophthalic polyester SMC, gas yields of 8–13 wt.% can be sufficient to provide the energy requirements of the process plant. Liquid yields of 9–16 wt.% are nonpolluting liquid fuels with a high gross calorific value of 36.8 MJ kg<sup>-1</sup>. About 40 wt.% of such liquids could be used as petrols, and the remaining 60 wt.% could be mixed with fuel oils. The solid residues of 72–82 wt.% can be recycled in BMC with no detrimental effect on the BMC mechanical properties.

To summarize this section devoted to recycling technologies, it turns out in general that, as was evidenced by Buggy *et al.* (1995), an optimal recycling strategy has to be defined for each specific material combination. These authors have shown that solvent recycling was appropriate for carbon fiber/PEEK APC-2, whereas mechanical recycling was interesting in the case of polyester/glass prepreg off-cuts, and solvent swelling was used for an aramid fiber/epoxy composite. In the case of mechanical recycling, most studies tend to indicate that fiber attrition is the dominant factor contributing to a drop in mechanical properties, at least in the short-term. In the long-term, however, the durability of mechanically recycled composites depends, to a larger extent, to the degradation state of matrix and interface. The development of reliable components using composite regrind is not free of costs, and clearly requires in-depth quantitative performance assessments. The final statement follows Tesoro and Wu (1995), who clearly emphasize the need for long-range programs devoted to design for recycling on the one hand, and multidisciplinary research programs to develop a new generation of polymers with built-in recovery potential, on the other.

## 2.33.5 INTRODUCTION TO LIFE CYCLE ASSESSMENT OF COMPOSITES

### 2.33.5.1 What is Life Cycle Assessment?

Environmental life cycle assessment (LCA) is a tool to assess the environmental impact of products over the whole product life cycle, and is usually performed in three phases (SETAC, 1993) followed by an improvement assessment or interpretation procedure (Jolliet and Crettaz, 1997). According to Ryding (1994), LCA is

mainly applied to internal analyses of products, to achieve improvements, as well as to compare alternative products. For comprehensive information, the reader is referred to the works of the Society of Environmental Toxicology and Chemistry (SETAC, 1993) and the Center of Environmental Science in the Netherlands (CML, 1994; Heijungs, 1992). Two cases studies are presented to illustrate the application of LCA where glass reinforced composites are compared to steel and aluminum on the one hand, and to natural fiber reinforced composites on the other.

#### 2.33.5.1.1 *Goal definition, scope, and functional unit*

The goal definition defines the aim and the scope of the study as well as the function and functional unit of the studied product. The scope defines the functional boundaries, that is, the life cycle steps to be considered in the analysis, and the type of impacts that will be accounted for. It further involves geographical boundaries and temporal boundaries. The latter obviously depends on the lifetime of the product; it also depends on the lifetime of the selected emissions. The functional unit relates to the service provided by the use of the product and, as such, is a key feature of any LCA. In most cases, the functional unit should be distinguished from the production unit. As an example of a functional unit, let us consider a composite panel used in sandwich structures for thermal and acoustic insulation, for instance in buildings. The production unit would typically be one square meter of the composite, whose primary function would be to give structural stiffness to the sandwich. Additionally, secondary functions of the panel would be to integrate fixtures for assembly and to offer decorative alternatives. The production unit is expressed in this example in  $m^2$ . The functional unit, however, considers the service provided by such composite panel, that is, to provide thermal and noise insulation for a given lifetime, which would typically be of the order of several tens of years. It will therefore be expressed in terms of  $m^2$  year.

#### 2.33.5.1.2 *Inventory analysis*

The inventory lists pollutant emissions and resources consumption attributed to the product system defined in the preceding step. The inventory process is often time-consuming, and finds help from databases implemented for instance in ecodesign tools.

#### 2.33.5.1.3 *Impact assessment*

The impact assessment assesses the environmental impact and is composed of three parts:

(i) The *classification* step determines the pollutant emissions contributing to each impact category or problem type (greenhouse effect, human toxicity, ecotoxicity, etc.).

(ii) The *characterization* step weighs and quantifies the impact of the emissions within each category.

(iii) The *valuation* step assesses the relative importance of each impact category by determining the damages on safeguard subjects and the respective societal values of these damages and subjects.

#### 2.33.5.1.4 *Improvement analysis*

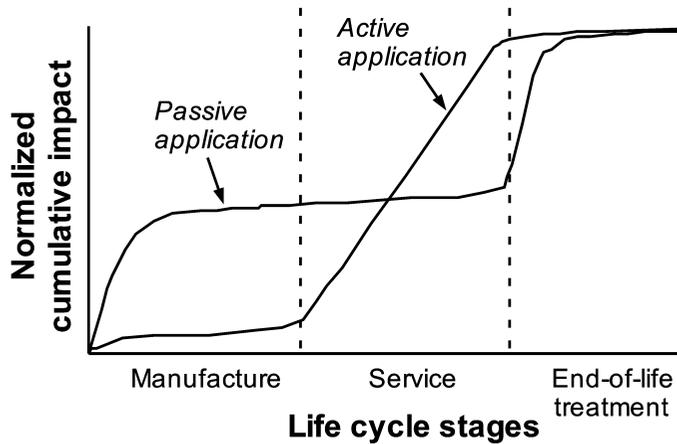
The aims of the improvement analysis are to determine environmental weak points in the production system as well as available technologies for improvements and organizational measures to accomplish such changes. In this phase, sensitivity studies and uncertainty analyses are performed together with improvement assessment.

#### 2.33.5.1.5 *Key issues in life cycle assessment*

It is generally recognized that a screening approach, where one ignores all effects contributing to less than a given fraction of the total impact, for example, 5%, should be performed prior to carrying out a more detailed LCA. Explicit definitions of the system function and boundaries, including functional unit, are essential elements in the analysis. Further key issues include allocation procedures and sensitivity analyses to determine the reliability of the data (see, for instance, the related publication of the Center of Environmental Science, CML, of the Leiden University, 1994). Finally, the LCA tool finds its usefulness when the interpretation phase enables the selection of more environmentally friendly materials and technologies.

#### 2.33.5.1.6 *Active and passive applications*

By definition, an environmentally active product mainly impacts the environment during service, contrary to an environmentally passive product, for which the main impacts are during manufacture and end-of-life treatment. The cumulated life cycle impacts of these two types of products would be such as sketched in Figure 10.



**Figure 10** Normalized cumulative impact of environmentally active (e.g., automotive) and passive (e.g., furniture) applications.

### 2.33.5.2 Life Cycle Assessment of Recycling

Use of the life cycle assessment method as a decision-making tool is in constant progress. We would like to point out here important factors to be accounted for when planning a recycling operation for composite materials. Dominant direct contributions to the environmental impact of recycling are likely to arise during collection of end-of-life parts, with its corresponding transportation burden, then during the reprocessing operation, and eventually during further transportation. As will be detailed in the following case studies, and if one excludes the environmental effects of transportation, the impact of producing secondary (i.e., recycled) materials is generally lower than that of primary materials, due to savings in feedstock extraction and refining processes. This fact is determinant in the case of aluminum, as seen in the corresponding material intensities reported in Table 1. As a consequence, there is a widespread belief that increasing recycling levels, that is, the fraction of secondary material in a given application, will systematically lead to an overall reduction in environmental load, in spite of the fact that such linear interpolation only provides a lower bound for the impact. Indeed, it does not account for nonlinear effects, resulting for instance from the increasing environmental impacts of revitalization (in order to maintain the quality of the recycled material) at higher recycling rates. An example of such nonlinearity has been reported for paper recycling (Schmidt and Fleischer, 1997). In the case of composites, these effects would typically correspond to the use of stabilizers and compatibilizers to overcome degradation of the polymer matrix and its probable contamination with foreign inclusions. Other nonlinearities arise when considering the logistics of waste manage-

ment, the environmental impact of which is essentially determined by transportation (Ishikawa, 1997). Higher recycling rates are obviously associated with a rapid increase in transportation distance that is proportional to the environmental impact. Efforts in integrated waste management were found to lower this contribution to the total impact (e.g., Schmidt and Fleischer, 1997). Several approaches for an optimum recycling network can be found in the studies of Eyerer and co-workers (Bohnacker *et al.*, 1995; Saur *et al.*, 1997), Schwarz and Steininger (1997), Everett *et al.* (1998), and Newell and Field (1998), who stress the importance of how to allocate inputs and outputs between primary and secondary materials.

### 2.33.5.3 Case Study of Components for Transportation Applications

This case study considers a hypothetical structural component developed for transportation applications. An example of such a component would be the front end of a car, although some of the materials selected for comparative purposes might not be relevant to the state-of-the-art technology for front-ends. Nonetheless, this case study is intended to illustrate the trade-offs which arise when optimizing both technology and environmental impacts in the case of an active product, as was defined in the preceding section. Few of such analyses have been published, and in-depth comparative analyses can be found in the work of Eyerer *et al.* (1994) and Bohnacker *et al.* (1995). Most of the data used in the inventory analysis was found in studies of Renard *et al.* (1994) and Young and Vanderburg (1994).

**Table 5** Material selection for the life cycle assessment of a structural component.

<i>Material</i>	<i>Weight</i> (kg)	<i>Production yield</i> (%)	<i>Recycling potential</i> (%)	<i>Price</i> (SFr/kg)
Steel sheet	10	65	90	0.5
Polyester composite (SMC)	7.0	100	20	3
Thermoplastic composite (GMT)	4.5	100	40	4
Aluminum	3.8	65	90	2

Sources: Renard *et al.*, 1994; Young and Vanderburg, 1994.

**Table 6** Energy consumption (MJ, boldface) and CO<sub>2</sub> emissions (kg, italics) of selected materials related to the life-cycle of a structural component.

	<i>Steel sheet</i>		<i>SMC</i>		<i>GMT</i>		<i>Al</i>	
Extraction of raw materials	<b>388</b>	<i>29</i>	<b>378</b>	<i>6</i>	<b>422</b>	<i>9</i>	<b>1315</b>	<i>224</i>
Recycling of materials	<b>110</b>	<i>8</i>	<b>49</b>	<i>3</i>	<b>50</b>	<i>4</i>	<b>292</b>	<i>23</i>
Manufacture of part	<b>171</b>	<i>12</i>	<b>41</b>	<i>3</i>	<b>42</b>	<i>3</i>	<b>133</b>	<i>8</i>
Service 100 000 km	<b>1423</b>	<i>85</i>	<b>995</b>	<i>60</i>	<b>640</b>	<i>39</i>	<b>541</b>	<i>34</i>
Total, 0% recycling	<b>1982</b>	<i>126</i>	<b>1414</b>	<i>69</i>	<b>1104</b>	<i>51</i>	<b>1989</b>	<i>266</i>
Total, 100% recycling	<b>1704</b>	<i>105</i>	<b>1085</b>	<i>66</i>	<b>732</b>	<i>46</i>	<b>966</b>	<i>65</i>

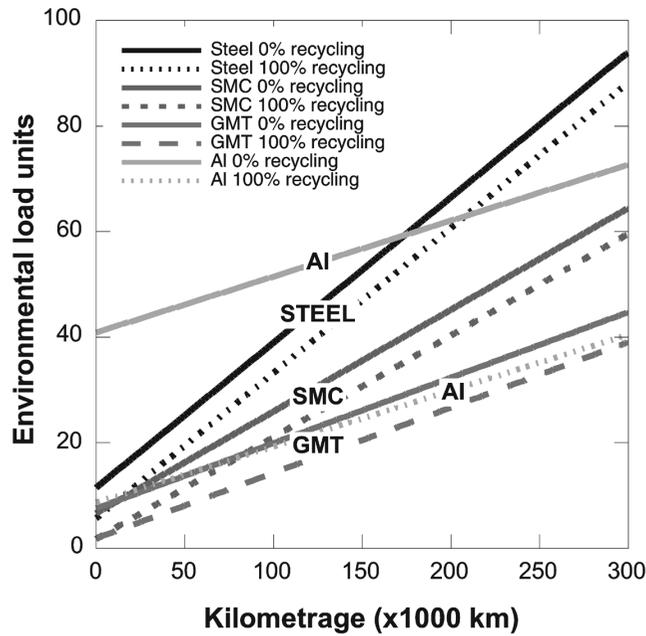
### 2.33.5.3.1 Materials selection and functional unit

The four materials selected are steel, aluminum, a thermoplastic composite (polypropylene-based GMT (see Chapter 2.27, this volume), for glass mat thermoplastic), and a thermoset composite (polyester-based SMC (see Chapter 2.22, this volume), for sheet molding compound), as specified in Table 5. The steel component is considered to be the reference material, and is attributed an arbitrary weight of 10 kg. The corresponding weight of the component was calculated for the two composite materials, with the criteria of constant equivalent bending stiffness per weight of material,  $E^{1/3}/\rho$ , where  $E$  is the Young's modulus and  $\rho$  is the density (Ashby, 1992). The weight of the aluminum part was set to be equal to 3.8 kg (Renard *et al.*, 1994). In addition, Table 5 specifies the production yield and the recycling potential for each material type, as well as its typical market cost. The recycling potential represents the fraction of regrind that is incorporated in the virgin material to produce a new part, according to the technical state-of-the-art (Furrer, 1995; Kelderman, 1995).

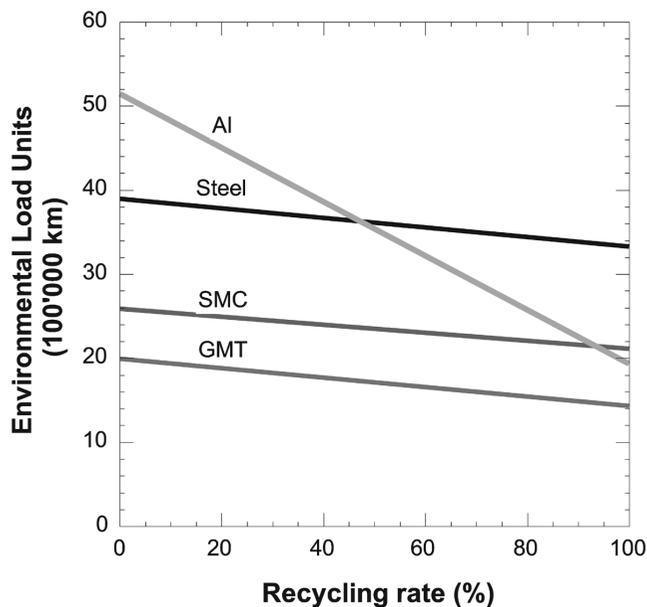
The production unit is one component, and is expressed in terms of its weight. The functional unit is the component for a given service, say 200 000 km, which would correspond to  $7 \text{ kg} \times 200\,000 \text{ km}$  for the SMC part. Two functional boundaries are considered as alternative scenarios to compare a nonrecycling option with a hypothetical 100% recycling option.

### 2.33.5.3.2 Energy and CO<sub>2</sub>

For the sake of simplicity, the LCA considers only energy requirements and CO<sub>2</sub> emissions. The environmental impact, expressed in "environmental load units" (ELU, Ryding, 1994), is calculated according to the EPS method using the equivalence of 0.014 ELU/MJ for the gross energy requirements (GER) and 0.088873 ELU/kg equivalent CO<sub>2</sub> for the global warming potential (GWP). A marginal weight gain, that is, the savings in fuel consumption during the use phase due to reduced weight, was assumed to be equal to 0.04 ml/kg.km (Maggee, 1982). The results of the LCA inventory for both 0 and 100% recycling scenarios are reported in Table 6, where a service of 100 000 km was considered. Figure 11 represents graphically the linear evolution of the overall impact, expressed in ELU units, with kilometrage. The initial intercept corresponds to the production impact, and the slope of the line corresponds to the impact during service, which is simply proportional to the weight of the component. Despite the simplifications used in the inventory and impact assessment, the calculated environmental profiles provide useful information to compare composites with steel and aluminum. First and foremost, the driving force to lower weight in transportation applications is striking. Similarly, the environmental benefit of recycling aluminum is considerable, whereas it is less obvious for steel as well as for the composite materials. This remark is highlighted in Figure 12, where the effect of recycling rate on



**Figure 11** Environmental impact of selected materials for a structural automotive component vs. kilometrage during service, for 0% and hypothetical 100% recycling scenarios. See text for details.

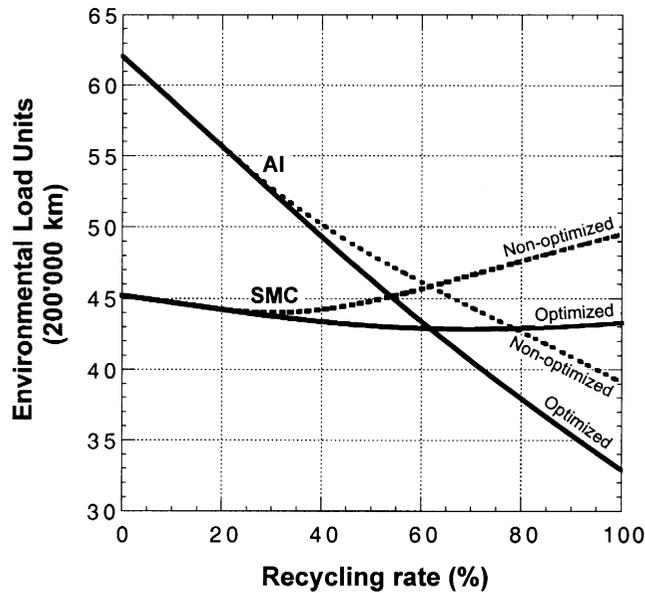


**Figure 12** Environmental impact of selected materials for a structural automotive component vs. recycling rate, for a service of 100 000 km. See text for details.

environmental impact is calculated for a service of 100 000 km from a linear interpolation of the data obtained for 0 and 100% recycling scenarios.

As was previously pointed out, high recycling rates are associated with nonlinear effects, with corresponding rapid increase in environmental impact. Figure 13 reproduces a simulation carried out for the aluminum and SMC composite

materials. The calculation is based on simulated annealing principles found to be equivalent to optimizing travel distances, and treated as the famous traveling salesman problem (see, for instance, the compilation of Lawler, 1990). It uses as a reference the average transportation distances for waste management documented in the study of Schmidt and Fleischer (1997). The “worst case” calculation corresponds to a



**Figure 13** Environmental impact of selected materials for a structural automotive component vs. recycling rate, for a total service of 200 000 km, and under two scenarios of collection logistics. See text for details.

nonoptimized route between cities of different sizes and arbitrary locations. The “best case” calculation performs in a first step a local route optimization between a number of small cities and one large city, and then calculates the remaining route between the large cities. Although the exact values reported in the figure should be taken with caution, their magnitude is qualitatively comparable to data published elsewhere (Schmidt and Fleischer, 1997), and thus provide useful information. In the case of aluminum, it is almost always beneficial to use secondary material, as its environmental impact is by far smaller than that of primary aluminum. By contrast, the optimal recycling rate for the composite material clearly depends on the logistics scenario. It is approximately 30% for nonoptimized collection, and of the order of 70% if the collection logistics are optimized, that is higher than the current practices. To summarize, the main conclusions drawn from this case study are twofold:

- (i) Very high recycling rates are not necessarily environmentally friendly.
- (ii) The environmentally optimal recycling rate is often higher than the actual recycling rate.

#### 2.33.5.4 Case Study of Glass-fiber and Natural-fiber Reinforced Thermoplastics

As was introduced in Section 2.33.1, increasing the use of renewable resources is one of the three routes towards sustainable resource management, providing this increase is based on

environmental assessment, to define in particular optimal product composition. This case study is based on recent work where the environmental impact of transport pallets made of glass-fiber-reinforced polypropylene was compared to natural-fiber reinforced polypropylene during a cycle of manufacture, use, and recycling (Gfeller-Laban and Nicollier, 1999; Lundquist *et al.*, 1999). Particular attention is paid to the effect of fiber content on energy consumption, which reflects to a good extent the overall impact. Over one million pallets are made per year and 150 million tons of wood pallets are sent to landfill each year in the US alone (Marsh, 1998). Thermoplastic pallets are a viable alternative since they have higher longevity and require less maintenance, thus representing high potential for cost savings by product life extension.

##### 2.33.5.4.1 Materials selection and functional unit

Traditional E-glass fibers (GF; density 2.6, Young’s modulus 72 GPa) and a standard grade of polypropylene (PP; density 0.905, Young’s modulus 1.15 GPa) were selected as the reference materials. The natural fibers were obtained from China reed, a perennial grass, characterized by a fast growth due to a particularly effective photosynthesis (Werner and Köhler, 1994), and whose production reaches ca. 20 tons/ha/y of biomass. The China reed fibers (CR; density 1.05, Young’s modulus 30 GPa) were obtained through grinding and sieving,

**Table 7** Composition and properties of the glass-fiber reinforced PP (GF) and the China reed fiber reinforced PP (CR) composite pallets, according to the three stiffness scenarios.

	Scenario 1: low stiffness		Scenario 2: medium stiffness		Scenario 3: high stiffness	
	GF	CR	GF	CR	GF	CR
Composite stiffness (MPa)	8.2	8.2	15.3	15.3	20.3	20.3
Fiber volume fraction (%)	10	24.6	20	49.1	27	66.3
Fiber weight fraction (%)	24.2	27.4	41.8	52.8	51.5	69.5
Pallet weight (kg)	15	13.1	15	11.8	15	11.0
Pallet volume (m <sup>3</sup> )	0.0140	0.0140	0.0121	0.0121	0.0110	0.0110

with a yield of 70%. The remaining 30% residues are presently landfilled.

The functional unit is one composite pallet, defined by its shape, i.e., its volume, and its stiffness, further satisfying service requirements during 5 years. To compare the two types of reinforcements, it is crucial that the corresponding pallet have the same volume and mechanical properties. The glass-fiber reinforced pallet was selected as the reference product, with a weight of 15 kg. Three scenarios were envisaged:

(i) low-stiffness composite pallet ( $E = 8.2$  MPa), where the reference pallet has a glass-fiber volume fraction of 10%.

(ii) medium-stiffness composite pallet ( $E = 15.3$  MPa), where the reference pallet has a glass-fiber volume fraction of 20%.

(iii) high-stiffness composite pallet ( $E = 20.3$  MPa), where the reference pallet has a glass-fiber volume fraction of 27%.

The composition of the China-reed fiber reinforced pallets was simply calculated using the rule of mixtures as a first approximation, so that all pallets with a given fiber fraction have the same stiffness and same volume, with the condition that all glass-fiber reinforced pallets weigh 15 kg. The composition and weight of all types of pallets are reported in Table 7. In all instances, due to the lower density of the natural fibers, the weight of the corresponding pallet is less than that of the glass-fiber reinforced alternative. Surprisingly, the weight of the natural fiber reinforced pallet decreases with increasing fiber fraction, while the density of the fibers is slightly higher than that of the polymer matrix. This decrease is contrary to the glass-fiber case, and results from the decrease in volume of the China reed pallet.

#### 2.33.5.4.2 Impact assessment and sensitivity analysis

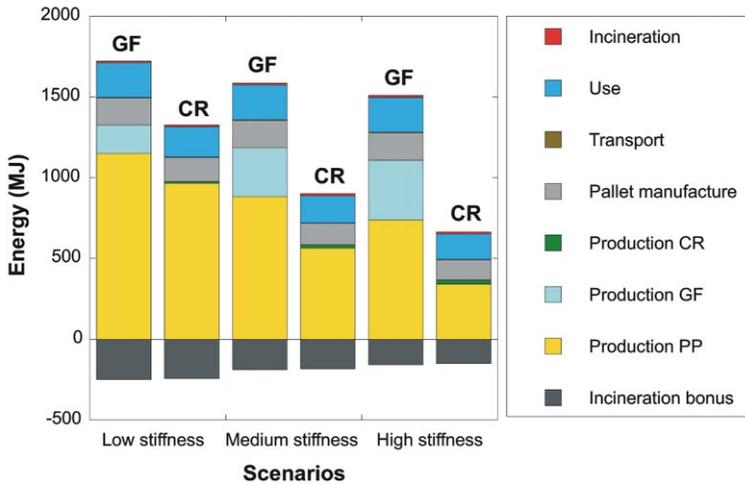
The environmental impact of the composite alternatives was assessed using the CST95 method (Jolliet and Crettaz, 1997 and sub-

mitted to *J. Risk. Anal.*), for the entire life cycle of the pallets: from agricultural production of China reed and production of glass fibers, grinding of China reed fibers, transport, production of polypropylene, pallet fabrication, pallet use, and pallet elimination by means of incineration with heat recovery. The energy consumption and emissions of over 50 pollutants in air, soil, and water determined in the inventory were reported to the functional unit. In the impact assessment, the pollutants were weighted with characterization factors enabling their summation into total impacts on resource consumption, human health, and terrestrial and aquatic ecosystems. Figure 14 shows the consumption of primary nonrenewable energy for the three scenarios.

Several remarkable conclusions can be drawn from these results. First, it is evident that the manufacturing stage of polypropylene is systematically the greatest contribution to the overall energy consumption. The implication of this is that higher fiber fractions, whether glass fibers or natural fibers, are beneficial from the energy consumption point of view. Previous work has shown that the same was true for all classes of impact indicators, at the exception of the human toxicity factor which slightly increases with increasing fiber fraction, and the eutrophication factor, in the case of the China reed fiber reinforced pallet (Gfeller-Laban and Nicollier, 1999). These results were confirmed by the CML impact assessment method (Heijungs, 1992).

Second, the contribution of China reed agricultural production to the overall energy consumption is negligible, and is by far smaller than that of the glass fibers. In spite of a higher contribution to eutrophication effects, all impact categories related to the China reed production have a lower contribution compared to the production of glass fibers.

It should finally be mentioned that the durability of the natural fiber composite could be a limitation when selecting this class of reinforcements. In this case study, a lifetime of 5 years



**Figure 14** Primary nonrenewable energy consumption for glass fiber/PP vs. China reed/PP composite transport pallets (after Gfeller-Laban and Nicollier, 1999; Lundquist *et al.*, 1999).

was considered for both types of composites. A sensitivity analysis revealed that the China reed fiber reinforced pallets have a lower environmental impact than the glass fiber reinforced pallets providing that their lifetime is at least 2.23 years.

### 2.33.6 CLOSURE AND PERSPECTIVES

Until mid-twentieth century, there was no serious consideration of the interaction between increasing industrialization and the ecosystem. The year 1952, with the introduction of the *Safe Minimum Standard of Conservation Principle* (SMS), marks a clear change in awareness on the vulnerability of the ecosystem. In the next two decades, the number of international events related to global environmental issues, whether conferences or government regulations, increased a considerable extent. In 1968, the *Intergovernmental Program on the Man and the Biosphere* (MAB) was launched after the Biosphere Conference of UNESCO, followed in 1970 by the US Clean Air Act, and the United Nations Conferences on the Law of Sea (UNCLOS). The *United Nations Environment Program* (UNEP) was created in 1972 during the Stockholm Conference on Human Environment. During the same year, the report “Limits to growth” of the Club of Rome and MIT and its *Standard World Model* were published. This rapid increase in environmental awareness had direct implications on the industry, which mainly reacted following “end of pipe” approaches. These were essentially dealing with depollution strategies, rather than cleaner production and pollution prevention actions, such

as the Polluter Pays Principle (PPP) instituted by the OECD, also in the year 1972. The 1980s have subsequently seen increasing development of design for environment and life cycle assessment tools, as described in this chapter.

During the 1990s, a novel concept emerged under the name *industrial ecology*, already envisioned in the 1950s, as recently reviewed by Erkman (1997). According to Ehrenfeld (1997), “industrial ecology is a new system for describing and designing sustainable economies. It offers guidelines to designers of products and the institutional structures in which production and consumption occur, as well as frameworks for the analysis of complex material and energy flows across economies.” In short, industrial ecology promotes systems where internal flows are greater than external flows, and, as such, integrates the three main topics discussed in this chapter, namely (i) durability analysis of composites, (ii) their sustainable design including recycling issues, and (iii) life cycle assessment. Recent studies in the field of industrial ecology with emphasis on material-related issues (e.g., Szekely and Trapaga, 1995; Frosch *et al.*, 1997) suggest that large environmental benefits can be achieved by closing material loops, which, as a reminder, is reached by extending product lifetime, by recycling materials, or by using renewable resources.

The wide spectra of applications using polymer composites nevertheless imply that an optimal loop-closing strategy has to be defined for each particular case. As reported in the preceding sections, considerable efforts are devoted to improve durability analyses, as also to develop reliable recycled and renewable composites. In the latter two fields, these efforts have been accompanied by the development of numerous

ecodesign tools, and there is no doubt that such activities will continue to expand. Finally, we would like to stress that more work is still needed to augment the integration among these key factors towards a sustainable use of resources, extensively discussed in the present work. Particularly, the issues of material quality, reliability, and durability, whether for virgin or recycled composites, should be enhanced in ecodesign practices, similarly to what is done for life cycle assessment. Such integration in the design stage would eventually offer a sound framework within which more durable composite materials may be developed.

## ACKNOWLEDGMENTS

The author would like to express his gratitude to Professor O. Jolliet of the EPFL Institute of Soil and Water Management for fruitful discussions on life cycle assessment.

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