Chapter 7

Case Study: Polymer Matrix Composites in Automobiles

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FINDINGS

The increased use of advanced structural materials may have significant impacts on basic manufacturing industries. The automotive industry provides an excellent example, since it is widely viewed as being the industry in which the greatest volume of advanced composite materials, particularly polymer matrix composites (PMCs), will be used in the future. Motivations for using PMCs include weight reduction for better fuel efficiency, improved ride quality, and corrosion resistance. Extensive use of composites in automobile body structures would have important impacts on methods of fabrication, satellite industry restructuring, and creation of new industries such as recycling.

The application of advanced materials to automotive structures will require: 1) clear evidence of the performance capabilities of the PMC structures, including long-term effects; 2) the development of high-speed, reliable manufacturing and assembly processes with associated quality control; and 3) evidence of economic incentives (which will be sensitively dependent on the manufacturing processes).

The three performance criteria applicable to a new material for use in automotive structural applications are fatigue (durability), energy absorption (in a crash), and ride quality in terms of noise, vibration, and harshness (generally related to material stiffness). There is emerging evidence from both fundamental research data and field experience that glass fiber-reinforced PMCs can be designed to fulfill these criteria.

At present, the successful application of PMCs to automobile body structures is more dependent on quick, low-cost processing methods and materials than it is on performance characteristics. There are several good candidate methods of production, including high-speed resin transfer molding, reaction molding, compression molding, and filament winding, At this time, no method can satisfy all of the requirements for production; however, resin transfer molding seems the most promising.

Clearly, the large-scale adoption of PMC construction for automobile structures would have a major impact on fabrication, assembly, and the supply network. The industry infrastructure of today would completely change; e.g., the multitude of metal-forming presses would be replaced by a much smaller number of molding units, multiple welding machines would be replaced by a limited number of adhesive bonding fixtures, and the assembly sequence would be modified to reflect the tremendous reduction in parts. This complete revamping of the stamping and body construction facilities would clearly entail a revolution (albeit at an evolutionary pace) in the industry. However, there would probably not be a significant impact on the size of the overall labor force or the skill levels required.

Extensive use of PMCs by the automotive industry would necessitate the development of completely new supply industries geared to providing inexpensive structures. It is anticipated that such developments would take place through two mechanisms. First, current automotive suppliers, particularly those with plastics expertise, would unquestionably expand and/or diversify into PMCs to maintain and possibly increase their current level of business. Second, the currently fragmented PMCs industry, together with raw material suppliers, would generate new integrated companies with the required supply capability. In addition, completely new industries would have to be developed, e.g., a comprehensive network of PMC repair facilities, and a recycling industry based on new technologies,

Economic justifications for using PMCs in automotive are not currently available. The economics will not become clear until the manufacturing developments and associated experience are in hand. Economics, customer perception, and functional improvements will dictate the eventual extent of usage. Present economic indicators suggest that PMCs would initially be used only for low-volume vehicles, and thus the most likely scenario would be limited usage of these materials. It is clear that a significant fraction of annual U.S. auto production would have to convert to large-scale PMC usage before a major impact is felt by such related industries as the steel industry, tool and die manufacturers, and chemical manufacturers. For example, it would take production of 500,000 largely-PMC vehicles per year to cause a 3 percent decrease in automotive steel use. The corresponding effect on these industries, therefore, would be minor.

INTRODUCTION

The use of PMC materials in the United States in automotive applications has gradually evolved over the past two decades. With new materials and processing techniques being continuously developed within the U.S. plastics and automotive industries, there is potential for a more rapid expansion of these types of applications in the future. PMC applications, both for components and for major modular assemblies, appear to be a potential major growth area that could have a significant impact on the U.S. automotive industry and associated supply industries if the required developments result in cost-effective manufacturing processes.

Extensive research and development (R&D) efforts currently underway are aimed at realizing eight potential benefits of PMC structures for the U.S. automotive industry:

- weight reduction, which may be translated into improved fuel economy and performance;
- improved overall vehicle quality and consistency in manufacturing;
- part consolidation resulting in lower vehicle and manufacturing costs;
- improved ride performance (reduced noise, vibration, and harshness);
- vehicle style differentiation with acceptable or reduced cost;
- lower investment costs for plants, facilities, and tooling—depends on cost/volume relationships;
- corrosion resistance; and
- lower cost of vehicle ownership.

However, there are areas where major uncertainties exist that will require extensive research and development prior to resolution. For example:

- high-speed, high-quality manufacturing processes with acceptable economics;
- satisfaction of all functional requirements, particularly crash integrity and long-term durability;
- repairability;
- recyclability; and
- customer acceptance.

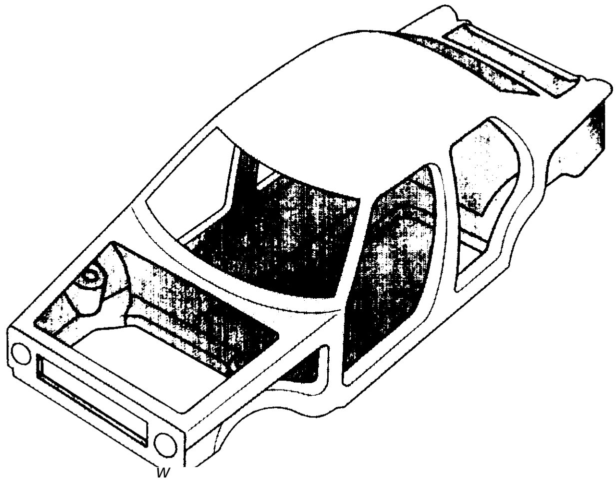
The purpose of this case study is to present scenarios showing the potential impact of PMCs on the U.S. automotive industry, its supplier base, and customers. These scenarios depict the effects likely to be generated by implementation of the types of materials and process techniques that could find acceptance in the manufacturing industries during the late 1990s, provided development and cost issues are favorably resolved,

To project the potential of PMCs for automotive applications, it is necessary to provide a reasonably extensive summary of the current state of these materials from the U.S. automotive industry's perspective. In particular, the specific types of PMCs showing the most promise for structural applications are described, as well as the most viable fabrication processes. The particular properties of greatest relevance to automotive applications are presented, together with an agenda for gaining the knowledge required before high confidence can be placed in the structural application of the materials.

[1] This chapter is based on a contractor report prepared for the Office of Technology Assessment, by P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., entitled "Impact of New Materials on Basic Manufacturing Industries—Case Study: Composite Automobile Structure, " 1987.

This case study illustrates the potential of PMCs by examining the case of a highly integrated PMC body shell, as depicted in figure 7-1. Basically, this body shell is the major load-bearing structure of the automobile. This basic structure, which does not include the hood, decklid, and doors, has been chosen as representative of the type of assembly that might be produced in moderate volumes as PMC materials begin to penetrate the U.S. automobile industry.

Figure 7-1.—Steel Body Shell Structure



SOURCE P Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study' Composite Automobile Structure," contractor report for OTA, 1987

BACKGROUND

The economic constraints in a mass-production industry such as the automotive industry are quite different from the aerospace or even the specialty-vehicle industry. This is particularly true in the potential application of high-performance PMC materials, which to date have primarily been developed and applied in the aerospace industry. At present, virtually all uses of plastics and PMCs in high-volume vehicles are restricted to decorative or semistructural applications.

Sheet molding compound (SMC) materials are the highest performance composites in general automotive use for bodies today. However, the most widely used SMC materials contain about 25 percent chopped glass fibers by weight and cannot really be classified as high-performance composites. Typically, SMC materials are used for grille-opening panels on many auto lines and closure panels (hoods, decklids, doors) on a few select models.

The next major step for PMCs in the automotive business is extension of usage into truly structural applications such as the primary body structure, and chassis/suspension systems. These are the structures that have to sustain the major road-loads and crash loads. In addition, they must deliver an acceptable level of vehicle dynamics such that the passengers enjoy a comfortable ride.

These functional requirements must be totally satisfied for any new material to find extensive application in body structures, and it is no small challenge to PMCs to meet these criteria effectively. These criteria must also be satisfied in a cost-effective manner. Appropriate PMC fabrication procedures must be applied or developed that satisfy high production rates but still maintain the critical control of fiber placement and distribution.

PMC body structures have been used in a variety of specialty vehicles for the past three decades; Lotus cars are a particularly well-known example. The PMC reinforcement used in these specialty vehicles is invariably glass fiber, typically in a polyester resin. A variety of production methods have been used but perhaps the only thing they have in common is that all the processes are slow, primarily because of the very low production rate of vehicles (typically, up to a maximum of **5,000** per year).[2] Thus, there has been no incentive to accelerate the development of these processes for mass production. The other common factor among these specialty vehicles is the general use of some type of steel backbone or chassis, which is designed to absorb most of the road loads and crash impact energy. Thus, while the composite body can be considered somewhat structural, the major structural loads are not imposed on the composite materials.

Current vehicles that include high volumes of fiber-reinforced plastic (FRP) have been designed specifically for FRP materials, as opposed to being patterned after a steel vehicle. Consequently, it is not possible to make a direct comparison between an FRP vehicle and an identical steel vehicle to derive baseline characteristics. Perhaps the best comparison would be between the prototype "Graphite LTD" built by Ford, and a production steel vehicle.[3] The vehicle was fabricated by hand lay-up of graphite fiber prepreg.

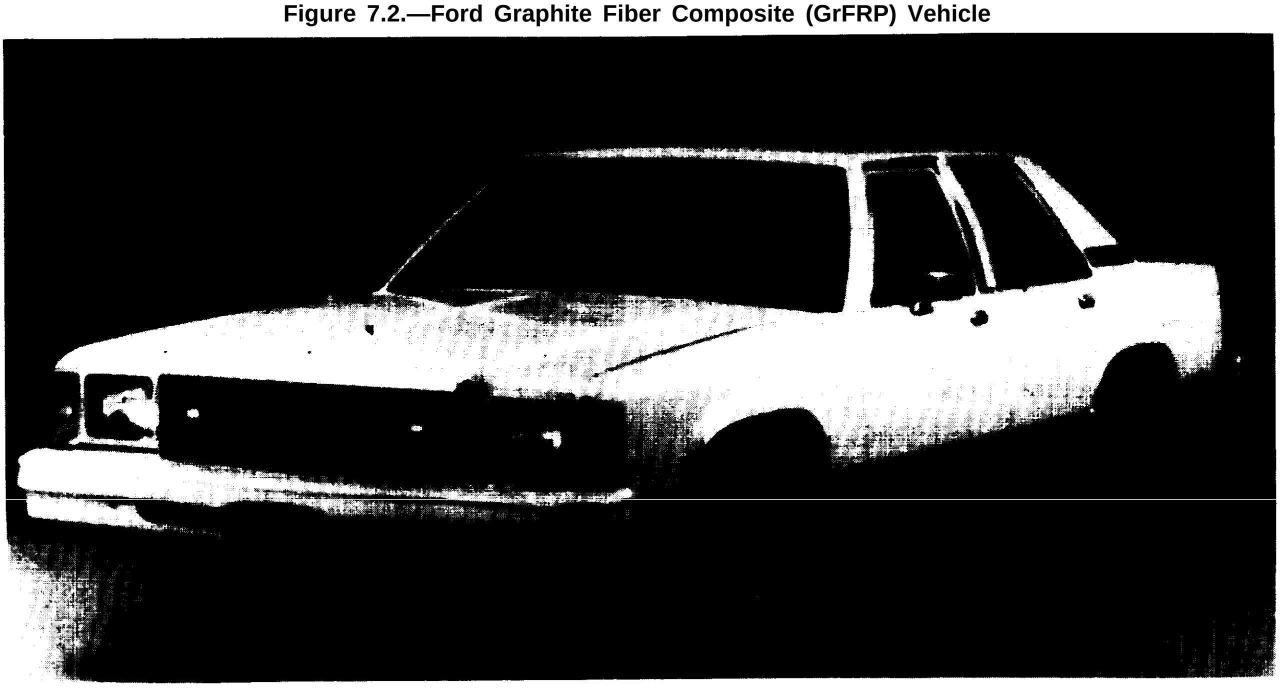
This graphite fiber-reinforced plastic (GrFRP) auto is shown in figure 7-2, and an exploded schematic showing its composite parts is presented in figure 7-3. The weight savings for the various structures are given in table 7-1. While these weight savings (of the order of 55 to 65 percent) might be considered optimal because of the use of low density graphite fibers, other more cost-effective fibers are stiff enough to be able to achieve a major portion of these weight savings (with redesign).[4] Although the GrFRP vehicle weighed 2,504 pounds compared to a similar steel production vehicle of 3,750 pounds, vehicle evaluation tests indicated no perceptible dif-

2 Ibid.

3P. Beard more, J.J. Harwood, and E.J. Horton, paper presented at the International Conference on Composite Materials, Paris, August 1980.

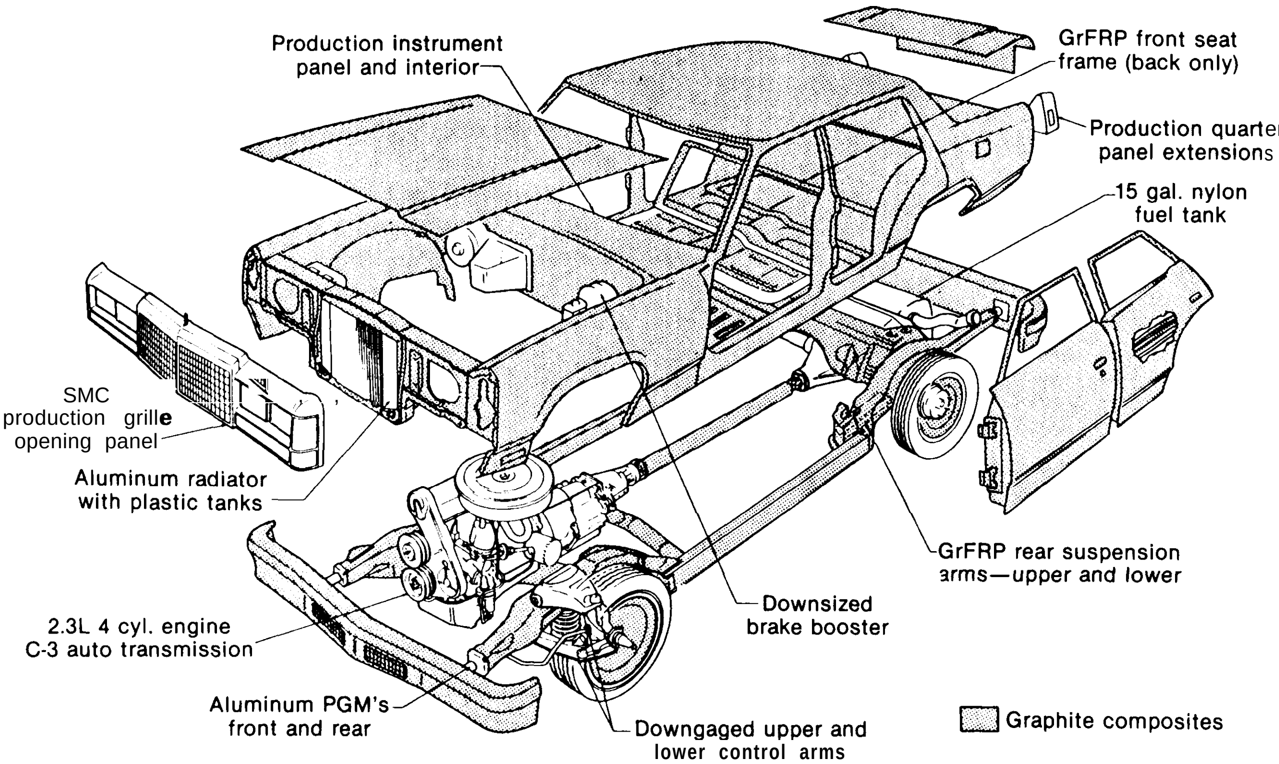
'Beard more, Johnson, and Strosberg, op. cit., footnote 1.

Figure 7.2.—Ford Graphite Fiber Composite (GrFRP) Vehicle



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987

Figure 7-3.— Ford GrFRP Vehicle With the Composite Components Shown



SOURCE: P Beardmore, C F Johnson, and G.G. Strosberq, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure, " contractor report for OTA, 1987

ference between the vehicles.[5] The GrFRP auto's ride quality and vehicle dynamics were judged at least equal to those of top-quality production steel LTD autos. Thus, on a direct comparison basis, a vehicle with an entire FRP structure was proven at least equivalent to a steel vehicle from a vehicle dynamics viewpoint at a weight level only 67 percent of the steel vehicle. b

The GrFRP auto clearly showed that high-cost fibers (graphite) and high-cost fabrication tech-

[5]Ibid,

[6]Ibid.

Table 7-1.—Major Weight Savings of GrFRP[a] Over Steel in Ford "Graphite LTD" Vehicle Prototype

	Weight in pounds		
Component	Steel	GrFRP	Reduction
Body-in-white	423.0	160.0	253.0
Front end	95.0	30.0	65.0
Frame	283.0	206.0	77,0
Wheel(s)	91.7	49.0	42.7
Hood	49.0	17.2	32.3
Decklid	42.8	14.3	28.9
Doors (4)	141.0	55.5	85.5
Bumpers (2)	123.0	44.0	79.0
Driveshaft	21.1	14.9	6.2
Total vehicle	3750	2504	1246

[a]GrFRP = Graphite Fiber-Reinforced Plastic

SOURCE: P. Beardmore, C F Johnson, and G.G. Strosberg, Ford Motor Co , "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987

Table 7-2.—Crash Energy Absorption Associated With Fracture of Composites Compared With Steel (typical properties)

Material	Relative energy absorption (per unit weight)
High performance composites	100
Commercial composites	60-75
Mild steel	40

[a]For example, graphite fiber-reinforced.
[b]For example, glass fiber. reinforced.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure, " contractor report for OTA, 1987 niques (hand lay-up) can yield a vehicle that is wholly acceptable in terms of handling, performance, and vehicle dynamics. However, crash and durability performance were not demonstrated, and these issues will need serious development work to achieve better-than-steel results. An even bigger challenge is to translate the GrFRP auto's performance into realistic economics through the use of cost-effective fibers, resins, and fabrication procedures.

Specialty autos of high PMC content use steel es the major load-carrying structure and are not generally priced on a competitive basis. Consequently, these vehicles cannot be used to develop guidelines for extensive PMC usage in high-volume applications.

The governing design guidelines for PMCs need to be further developed to ascertain, for instance, how to design using low-cost PMC materials, and to ascertain allowable for stiffness in situations where major integration of parts in PMCs eliminates a myriad of joints. The following sections summarize information on composite materials, performance criteria, and potential manufacturing techniques.

POLYMER MATRIX COMPOSITE MATERIALS

By far the most comprehensive property data have been developed on aerospace-type PMCs, in particular graphite fiber-reinforced epoxies fabricated by hand lay-up of prepreg materials. Relatively extensive databases are available on these materials, and it would be very convenient to be able to build off this database for less esoteric applications such as automobile structures. Graphite fibers are the favored choice in aerospace because of their superb combination of stiffness, strength, and fatigue resistance. Unfortunately for the cost-conscious mass-production industries, these properties are attained only at significant expense. Typical graphite fibers cost in the range of $25 per pound. There are intensive research efforts devoted to reducing these costs by using a pitch-based precursor but the most optimistic predictions are for fibers in the range of $5 to 10 per pound, which would still keep them in the realm of very restricted potential for consumer-oriented industries.[7]

The fiber with the greatest potential for automobile structural applications is E-glass fiber–currently, $0.80 per pound—based on the optimal combination of cost and performance.[8] Similarly, the resin systems likely to dominate at least in the near term are polyester and vinyl-ester resins based primarily on a cost/processability trade-off versus epoxy. Higher performance resins will only find specialized applications (in much the same way as graphite fibers), even though their ultimate properties may be somewhat superior.

The form of the glass fiber used will be very application-specific, and both chopped and continuous glass fibers should find extensive use. Most structural applications involving significant load inputs will probably use a combination of both chopped and continuous glass fibers with the particular proportions of each depending on the component or structure. Because all the fabrication processes likely to play a significant role in automotive production are capable of handling mixtures of continuous and chopped glass, this requirement should not present major restrictions.

One potential development likely to come about if glass fiber PMCs come to occupy a significant portion of the structural content of an automobile is the tailoring of glass fibers and corresponding specialty resin development. The size of the industry (each pound of PMC per vehicle translates into approximately 10 million pounds per year in North America) dictates that it would be economically feasible to have fiber and resin production tailored exclusively for the automotive market.[9] The advantage of such an approach is that these developments will lead to incremental improvements in specific PMC materials, which in turn should lead to increased applications and increased cost-effectiveness.

'Ibid.
8 Ibid.

9Ibid.

Although thermoset matrix PMCs will probably constitute the bulk of the structural applications, thermoplastic-based PMCs formed by a compression molding process may well have a significant but lesser role to play.

Most of the compression-molded thermoplastics in commercial use today tend to concentrate on polypropylene or nylon as the base resin. The reason is simply the economic fact that these materials tend to be the least expensive of the engineering thermoplastics and are easily processed. Both of these materials are somewhat deficient in heat resistance and/or environmental sensitivity relative to vehicle requirements for high-performance structures.

Other thermoplastic matrices for glass fiber-reinforced PMCs are under development, and materials such as polyethyleneterephthalate (PET) hold significant promise for the future. The extent to which thermoplastic PMCs will be used in future structures will be directly dependent on material developments and the associated economics.

PERFORMANCE CRITERIA

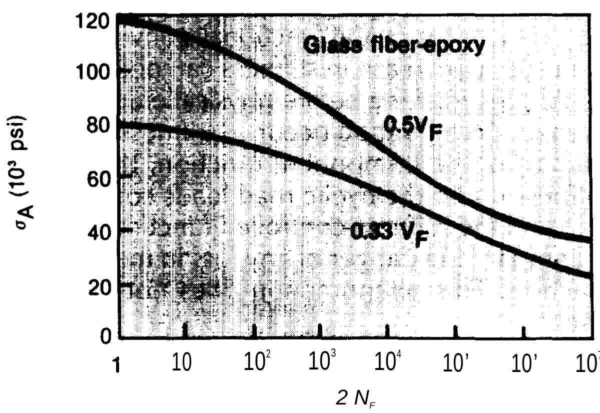
From a structural viewpoint, there are two major categories of material response critical to applying PMCs to automobiles. These are fatigue (durability) and energy absorption. In addition, there is another critical vehicle requirement, ride quality, which is usually defined in terms of noise, vibration, and ride harshness, and is generally perceived as directly related to vehicle stiffness and damping. Material characteristics play a significant role i n this category of vehicle response. These three categories will be discussed below.

Fatigue

The specific fatigue resistance of glass fiber-reinforced plastics (GIFRP) is a sensitive function of the precise constitution of the material. However, there are also preliminary research indications of the sensitivity to cyclic stresses. (For a further discussion of chopped and continuous glass fibers, see ch. 3.)

For unidirectional GIFRP materials, the fatigue behavior can be characterized as illustrated in figure 7-4. The most important characteristic in figure 7-4 is the fairly well-defined fatigue limit exhibited by these materials; as a guiding principle this limit can be estimated as approximately 35 to 40 percent of the ultimate strength.[10] A chopped glass PMC, by contrast, would have a fatigue limit closer to 25 percent of the ultimate strength and tends to produce less reliable fatigue test data. Figure 7-5 shows the scatter in fatigue test data for SMC.[11 12]

Figure 7-4.—Typical Fatigue Curves for Unidirectional Glass Fiber Composite (GIFRP) as a Function of Volume Fraction of Glass Fibers (V_F)



σ_A is defined as the amplitude of the cyclicly applied stress.
N_F is the number of cycles to failure.

Fatigue is described by the number of cycles to failure at a given cyclicly applied stress.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

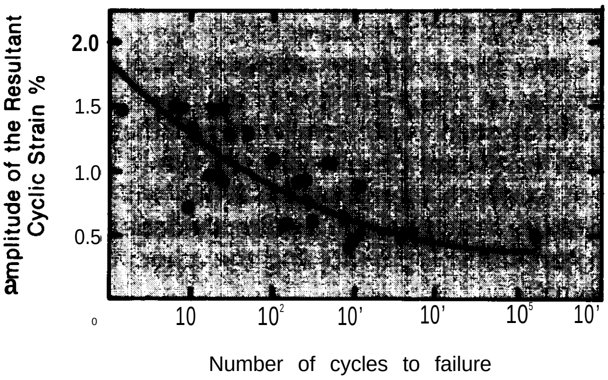
It is also important to note that the different failure modes in PMCs (in comparison to metals) can

[10] C.K. H. Dharan, *Journal of Materials Science*, vol. 10, 1975, pp. 1665-70.

[11] T.R. *Smith* and M.J. Owen, *Modern Plastics*, April 1969, pp. 124-29.

[12] A. Potem and Z. Hashim, *AIAA Journal*, vol. 14, 1976, pp. 868-72.

Figure 7-5.—Typical Fatigue Curve for Sheet Molding Compound



SMC exhibits significant scatter in fatigue test data.

SOURCE: P. Beardmore, CF. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

result in different design criteria for these materials, depending on the functionality involved. For instance, a decrease in stiffness can occur under cyclic stressing long before physical cracking and strength deterioration occur. If stiffness is a critical part of the component function, the loss in stiffness under the cyclic road loads could result in loss of the stiffness-controlled function with no accompanying danger of any loss in mechanical function. This phenomenon does not occur in steel.

As a guiding principle, it follows from the above that wherever possible, automotive structures should be designed such that continuous fibers take the primary stresses and chopped fibers should be present to develop some degree of isotropic behavior. It is critical to minimize the stress levels, particularly fatigue stresses, that have to be borne by the chopped fibers,

There is emerging evidence from both fundamental research data and field experience with PMC components that glass fiber-reinforced PMCs can be designed to withstand the rigorous fatigue loads experienced under vehicle operating conditions. The success of PMC leaf springs and SMC components attests to the capability of PMCs to withstand service environments.

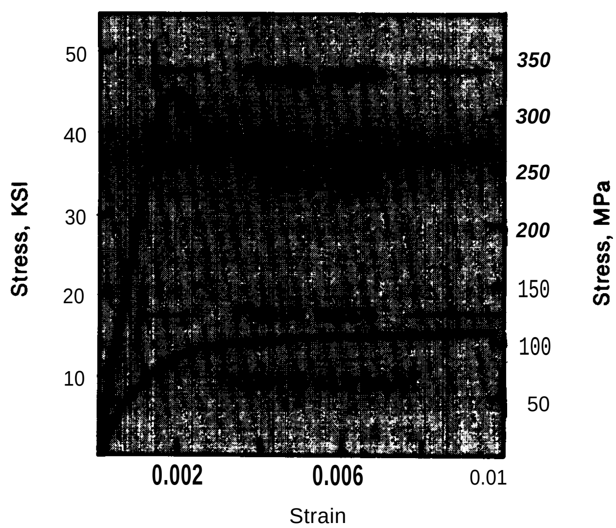
Although the data for all combinations of PMC materials are not yet available, a sufficient database is available such that conservative estimates can be developed and lead to reliable designs. It should be emphasized, however, that the mechanical properties of PMCs (much more than isotropic materials) are very sensitive to the fabrication process. It is imperative that properties be related to the relevant manufacturing technique to prevent misuse of baseline data.

Energy Absorption

The elongation (strain) behavior of a material under stress can indicate a great deal about the material's ability to absorb crash energy. Metals exhibit linear stress-strain behavior only up to a certain point, beyond which they plastically deform (see figure ***7-6).*** This plastic deformation absorbs a large amount of crash energy that could otherwise injure passengers.

The stress-strain curves of all high-performance PMCs are essentially linear in nature, as shown in figure 7-7. This resembles the behavior of brittle materials such as ceramics. Materials that are es-

Figure 7-6.—Tensile Stress-Strain Curves for Steel and Aluminum

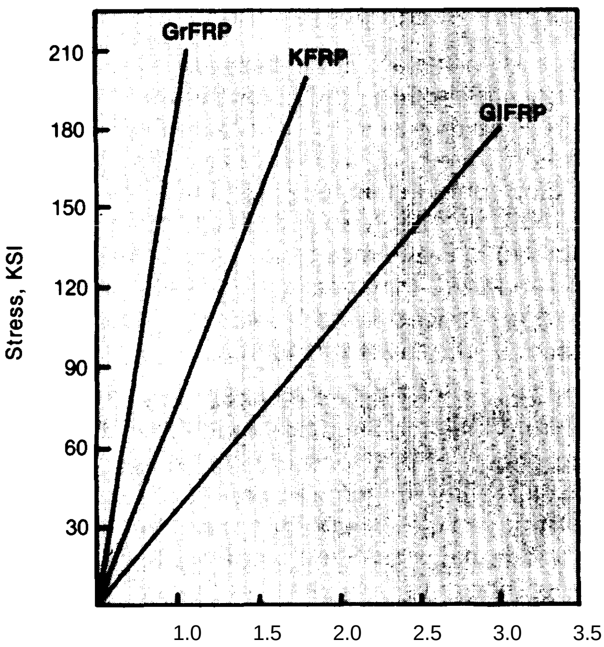


HRLC—hot rolled leaded carbon steel
1100-H12—strain hardened low alloy aluminum

The plastic region of metal stress-strain behavior absorbs crash energy.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-7.—Tensile Stress-Strain Curves for Graphite Fiber Composite (GrFRP), Kevlar Fiber Composite (KFRP), and Glass Fiber Composite (GlFRP)



The linearity of the curves means that these composites behave as brittle materials during fracture (cf fig. 7-6). There is no plastic region to absorb crash energy.

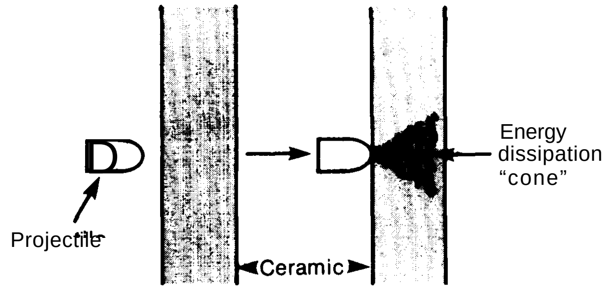
1 KSI = 10^3 psi

SOURCE' P Beardmore, C.F. Johnson, and G.G. Slrosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure, " contractor report for OTA, 1987

sentially elastic to failure (PMCs, ceramics) might be thought to have no capacity for energy absorption since no energy can be absorbed through plastic deformation. However, ceramics have been used for decades as armored protection against high-velocity projectiles.

In fact, energy absorption is achieved by spreading the localized impact energy into a high-volume cone of fractured ceramic material, as shown schematically in figure 7-8. A large amount of fracture surface area is created by fragmentation of the solid ceramic, and the impact energy is converted into surface energy resulting in successful protection and very efficient energy dissipation. Brittle materials can be very effective energy absorbers, but the mechanism is fracture surface energy rather than plastic deformation.

Figure 7.8.—Energy Dissipation Mechanism in Ceramics



Energy absorption occurs in ceramics and brittle PMCs by spreading local impact energy into a high-volume cone of fractured material.

SOURCE: P. Beardmore, CF. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987,

This analogy leads directly to the conclusion that high-performance PMCs may well be able to absorb energy by a controlled disintegration (fracture) process.

Evidence is emerging from laboratory test data on the axial collapse of PMC tubes that efficient energy absorption needed for vehicle structures can be achieved in these materials. A comparison between the collapse mechanisms of metals and PMCs is shown in figure 7-9. Glass fiber- and graphite fiber-reinforced PMCs behave as shown in figure 7-9(b). By contrast, PMCs using fibers consisting of highly oriented long-chain polymers (e.g., Kevlar) collapse in a metal-like fashion using plastic deformation as the energy absorbing mechanism. The fragmentation/fracture mechanism typical of glass fiber PMCs can be very effective in absorbing energy, as illustrated in table 7-2.

It is particularly significant that although high-performance, highly oriented PMCs provide the maximum energy absorption, commercial-type PMCs yield specific energy numbers considerably superior to metals. Thornton and coworkers have accumulated extensive data on energy absorption in composites.[13 14 15]

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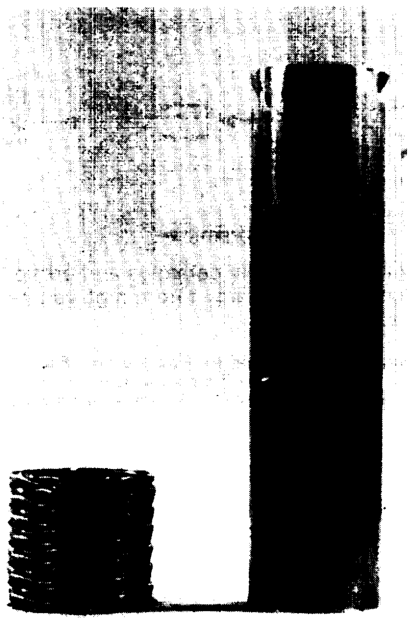
[13] P.H. Thornton and P.J. **Edwards,** *Journal of Composite Materials,* vol. 13, 1979, pp. 274-82.

[14] P.H. Thornton and P.J. Edwards, *Journal of Composite Materials,* vol. 16, 1982, pp. 521-45.

[15] P.H. Thornton, J.J. Harwood, and **P.** Beard more, International Journal of Composite Structures, 1985.

Figure 7-9.—C)ifferent Collapse Mechanisms in (a) Metal and (b) Composite Tubes, for Energy Absorption



a) energy, absorption by plastic deformation
b) fracture surface energy dissipation

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Im. pact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Virtually all the energy absorption data available to date have been developed for axial collapse of relatively simple structures, usually tubes. The ability to generate the same effective fracture mechanisms in complex structures is still unresolved. In addition, it is well known from observations on metal vehicles that bending collapse normally plays a significant part in the collapse of the vehicle structure, and it is consequently of considerable importance to evaluate energy absorption of composites in bending failure.

Just as in metals, little data are available on energy absorption characteristics in bending. There is no reason to believe that the energy absorption values of metals relative to PMCs in bending should change significantly from the ratios in axial collapse except that bending failure (fracture) in PMCs may tend to occur on a more localized basis than plastic bending in metals. If this does indeed occur, then the ratio could change in the favor of metals.

Other crash issues involve the capacity to absorb multiple and angular impacts and the long-term effects of environment on energy absorption capability. In general, practical data from a realistic, vehicle viewpoint are not yet in hand. An additional, significant factor is the consumer acceptance of these materials as perceived in relation to safety. A negative perception would be a serious issue on something as sensitive as safety, and better-than-steel crash behavior will be required before wide-scale implementation of PMCs can occur. Conversely, a positive perception would be a valuable marketing feature and provide an additional impetus for PMC applications.

Stiffness and Damping

Glass fiber-reinforced PMCs are inherently less stiff than steel. Some typical values for various types of PMC are listed in table 7-3. There are two offsetting factors to compensate for these material limitations. First, an increase in wall thickness can be used to offset partially the lesser material stiffness. Also, local areas can be thickened as required to optimize properties. Because PMCs have a density approximately one-third that of steel, a significant increase in thickness can be achieved while maintaining an appreciable weight reduction.

The second, and perhaps the major, offsetting factor is the additional stiffness attained in PMCs as a result of part integration. This integration leads directly to the elimination of joints, which results in significant increases in effective stiffness. It is becoming increasingly evident that this syn-

Table 7-3.—Typical Stiffness of Selected Composites

Material	Stiffness (10^6 psi)
Unidirectional GrFRP	20
Unidirectional GlFRP	6
Unidirectional Kevlar	11
XMC	4.5
SMC-R50	2.3
SMC-25	1.3

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Stromberg, Ford Motor Co. "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

ergism is such that structures of acceptable stiffness and considerably reduced weight are feasible in glass fiber-reinforced PMCs. As a rule of thumb, a glass FRP structure with significant part integration relative to the steel structure being replaced can be designed for a nominal stiffness level of 50 to 60 percent of the steel structure.[16] Such a design procedure should lead to adequate stiffness and to typical weight reductions of 20 to 50 percent.[17]

[16] Beardmore, Johnson, and Strosberg, Op. cit., footnote 1.
[17] Ibid.

The stiffness requirement for vehicles is normally dictated by vehicle dynamics characteristics. The historical axiom in the vehicle engineer's design principles is the stiffer the better. However, there are some intangible factors that enter the overall picture, in particular the damping factor.

It is an oversimplification to assume stiffness alone dictates vehicle dynamics, although it unquestionably dominates certain categories. Damping effects can play an equally significant role in many categories of body dynamics, and the fact that the damping of PMC materials considerably exceeds that of metals is relevant to the overall scenario. Most experts involved with PMC component/structure prototype development feel that some aspect of body dynamics (usually noise or vibration) is improved but few quantitative data are available to document the degree of improvement. If customers share this perception, PMCs will receive impetus for structural usage.

POTENTIAL MANUFACTURING TECHNIQUES

The successful application of PMCs to automotive structures is more dependent on the ability to use rapid, economic fabrication processes than on any other single factor. The fabrication processes must also be capable of close control of PMC properties to achieve lightweight, efficient structures.

Currently, the only commercial process that comes close to satisfying these requirements is compression molding of sheet molding compounds (SMCs) or some variant on this process. There are, however, several developing processes that hold distinct promise for the future in that they have the potential to combine high rates of production, precise fiber control, and high degrees of part integration.

The requirements for precise fiber control, rapid production rates, and high complexity demand that automotive processes be in the region of developing processes shown schematically in figure **7-10.** The three most important evolving processes are compression molding, high-speed resin transfer molding, and filament winding. Each of these processes is examined below.

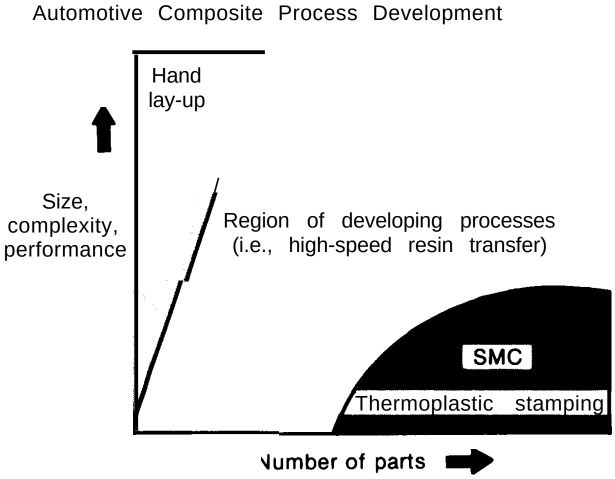
Compression Molding

This section discusses compression molding techniques; these are most often used with thermosetting resins but can be used with thermoplastic resins.

Thermosetting Compression Molding

Figure 7-11 presents a schematic of the SMC process, depicting both the fabrication of the SMC material and the subsequent compression molding into a component. This technology has been widely used in the automobile industry for the fabrication of grille-opening panels on many auto lines, and for some exterior panels on selected vehicles. Tailgates (figure 7-12), and hoods (figure 7-13) are examples on autos and light trucks; the entire cab on some heavy trucks (figure 7-14) is constructed in this manner.

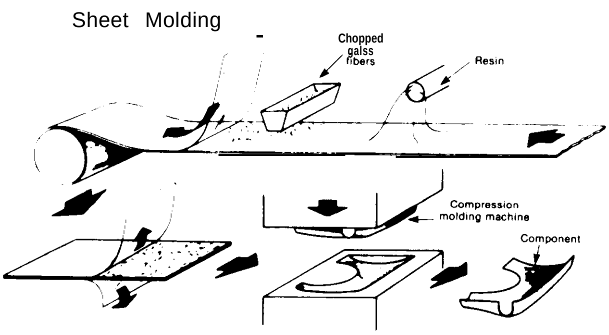
Figure 7-10.—Relationship Between Performance and Fabrication for Composites



Viable commercial processes must be able to produce a large number of high performance parts.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-11.—Sheet Molding Compound Material Preparation and Component Fabrication



SOURCE: P. Beardmore, CF. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

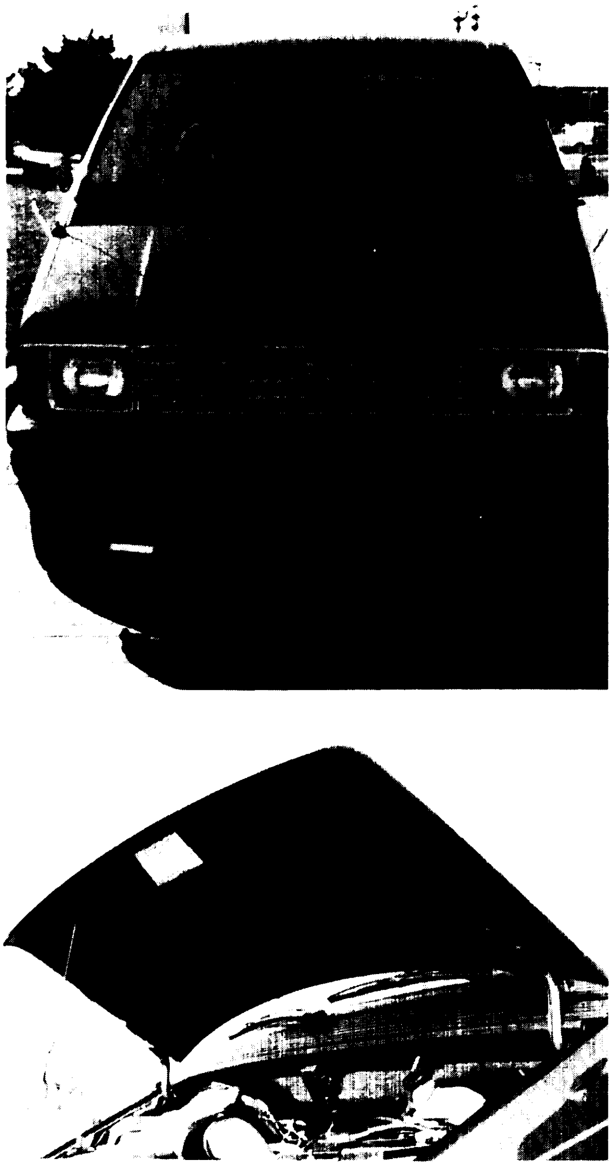
The process consists of placing sheets of SMC (1 to 2 inch long chopped glass fibers in chemically thickened thermoset resin) into a heated mold (typically at 3000 F) and closing the mold under pressures of 1,000 pounds per square inch (psi) for about 2 to 3 minutes to cure the material. Approximately 80 percent of the mold surface is covered by the SMC charge, and the material flows to fill the remaining mold cavity as the mold closes.

The above description of the SMC process delineates material primarily used for semistructural applications rather than high load bearing segments of the structure that must satisfy severe durability and energy absorption requirements.

Figure 7.12.—Typical Sheet Molding Compound Production Aerostar Tailgate

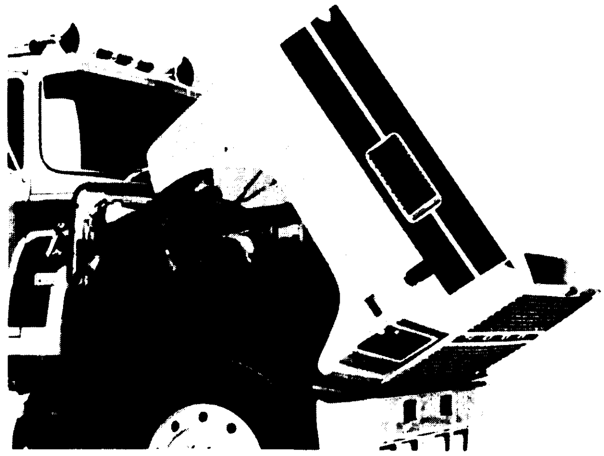
SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987, To sustain the more stringent structural demands, it is normally necessary to incorporate apprecia-

Figure 7-13.—Typical SMC Production Aerostar **Hood**



SOURCE P Beardmore, CF. Johnson, and G G Strosberg, Ford Motor Co , "impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure, " contractor report for OTA, 1987

Figure 7-14.—Typical SMC Truck Cab



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

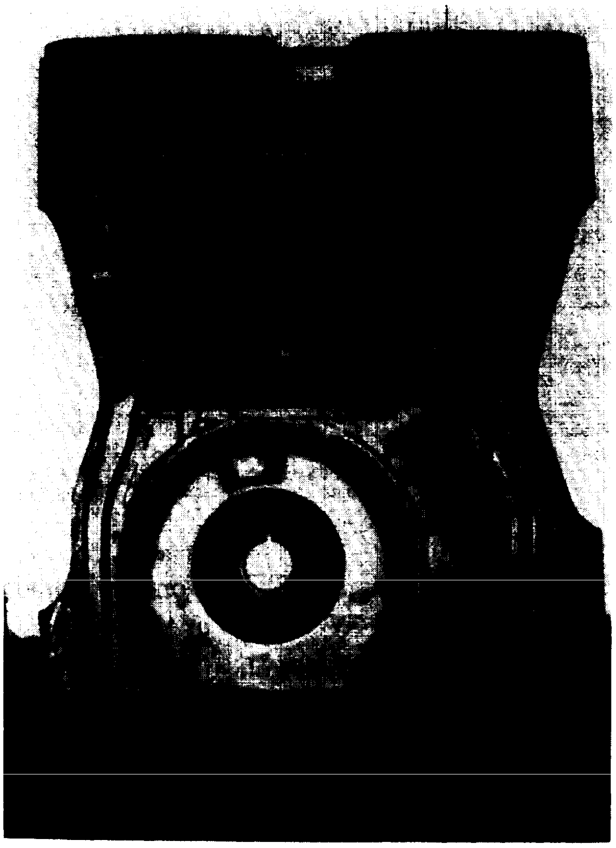
ble amounts of continuous fibers in predesignated locations and orientations.

The same basic SMC operation can be used to incorporate such material modifications either by formulating the material to include the continuous fibers along with the chopped fibers or by using separate charge patterns of two different types of material. The complexity of shape and degree of flow possible are governed by the amount and location of the continuous glass material. Careful charge pattern development is necessary for components of complex geometry. A typical example of a prototype rear floor pan fabricated by this technique is shown in figure 7-15.[18]

The limitations of compression molding of SMC-type materials in truly structural applications have yet to be established. Provided that continuous fiber is strategically incorporated, these materials promise to be capable of providing high structural integrity and may well prove to be the pioneering fabrication procedure in high load bearing applications. The state of commercialization of this process is advanced compared to other evolving techniques and this will provide a lead time for

[18] C. F. Johnson and N. G. Chavka, "An Escort Rear Floor Pan," *Proceedings of the 40th Annual Technical Conference,* Atlanta, GA, Society of the Plastics Industry, January 1985,

Figure 7-15.—Prototype Escort Composite Rear Floor Pan



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

compression molding to branch into higher performance parts.

Although compression molding of SMC-type materials is an economically viable, high production rate process in current use, there are some limitations inherent in the process. In the longer term, these will restrict applications and tend to favor the developing processes. For instance, material flow in the compression step results in imprecise control of fiber location and orientation. Typically, variations in mechanical properties of a factor of 2 throughout the component are not unusual based on an initial charge-pattern coverage of approximately 70 percent.

Such uncertainty in properties introduces reliability issues and encourages conservative designs that yield a heavier-than-necessary component or structure. Currently, extensive research efforts are underway to develop SMC-type materials that will allow 100 percent charge pattern coverage and that will attain high, uniform mechanical properties with minimal flow. These materials can also be molded at lower pressures on smaller capacity presses. Materials developments such as these may well make the newer breed of SMCs much more applicable to highly loaded structures than has hitherto been envisioned.

Another potential limitation of compression molding is the degree of part integration that is attainable. The basic strategy in PMC applications is to integrate as many individual (steel) pieces as possible to minimize fabrication and assembly costs (which offsets increased material costs) and to minimize joints (which increases effective stiffness). Compression molding requires fairly high molding pressures (about 1,000 pounds psi) and thus limits potential structures in area size and complexity (particularly in three-dimensional geometries requiring foam cores).

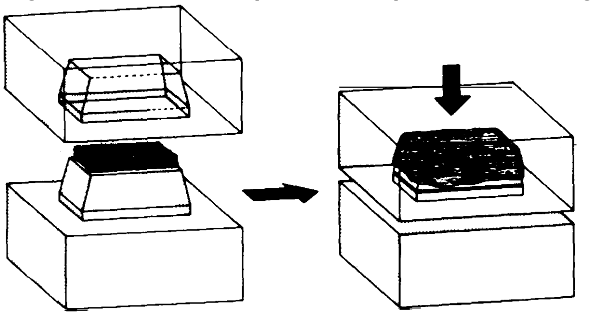
Consequently, although compression molding is likely to play a key role in the development of PMCs in structural automotive applications in the next decade, ultimately the process is unlikely to provide composite parts of optimum structural efficiency and weight. Nevertheless, compression molding is currently the only commercial PMC process capable of satisfying the economic constraints of a mass-production industry.

Thermoplastic Compression Molding

The process of thermoplastic compression molding (stamping) is attractive to the automotive industry because of the rapid cycle time and the potential use of some existing metal stamping equipment. Thermoplastic compression molding at its current level of development achieves cycle times of 1 minute for large components.

Figure 7-16 presents a schematic of the process. Typically, a sheet of premanufactured thermoplastic and reinforcement is preheated above the melting point of the matrix material and then rapidly transferred to the mold. The mold is quickly closed until the point where the material is contacted, and then the closing rate is

Figure 7-16.—Thermoplastic Compression Molding



SOURCE: P. Beardmore, C F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure" contractor report for OTA, 1987

slowed. The material is formed to shape and flows to fill the mold cavity much the same as thermoset compression-molded SMC. The material is cooled in the mold for a short period of time to allow the part to harden, and then the mold is opened and the component is removed.

Thermoplastic compression molding is currently used in automobiles to form low-cost semi-structural components such as bumper backup beams, seats, and load floors. Commercially available materials range from wood-filled polypropylene and short glass-filled polypropylene with relatively low physical properties, to continuous random glass-reinforced materials based on polypropylene or PET which offer somewhat higher physical properties. Other materials, based on highly oriented reinforcements and such resins as polyetheretherketone (PEEK) and polyphony - lene sulfide (PPS), are in use in the aerospace industry. These materials are expensive and are limited in their conformability to complex shapes.

Higher levels of strength and stiffness must be developed in low-cost materials before they can be used in structural automotive applications. Attempts have been made to improve the properties of stampable materials through the use of separate, preimpregnated, unidirectional reinforcement tapes. These materials are added to the heated material charge at critical locations to improve the local strength and stiffness. Using these materials adds to the cost of the material and increases cycle times slightly.

Although effective for simple configurations, location of the oriented reinforcement and reproducibility of location are problems in complex parts. To be most effective, these types of reinforcements ultimately will have to be part of the premanufactured sheet or be robotically applied. Current research is in progress in the area of thermoplastic sheet materials with oriented reinforcement in critical areas. For application to automotive structures, these materials will have to retain the geometric flexibility in molding (i. e., ability to form complex shapes with the reinforcement in the correct location) exhibited by today's commercial materials.

The question of part integration is a major issue in the expanded use of this process. The high pressures (1 ,000 to 3,000 psi) required limit the size of components that can be manufactured on conventional presses. Thermoplastic compression molding is also limited in its ability to incorporate complex three-dimensional cores required for optimum part integration.

If very large integrated structures are required from an overall economic viewpoint, thermoplastic compression molding will be restricted to smaller components such as door, hood, and deck lid inner panels in which geometry is relatively simple and/or part integration is limited due to physical part constraints. If very large-scale integration proves too expensive, then thermoplastic compression molding will exhibit increased market penetration. Ongoing long-range research in the area of low-pressure systems and incorporation of foam cores in moldings could significantly alter this outlook in the longer term.

High-Speed Resin Transfer Molding

Fabrication processes that permit precise fiber control with rapid processability would overcome many of the deficiencies outlined above. The use of some kind of preform of oriented glass fibers preplaced in the mold cavity, followed by the introduction of a resin with no resultant fiber movement would satisfy the requirements for optimum performance and high reliability.

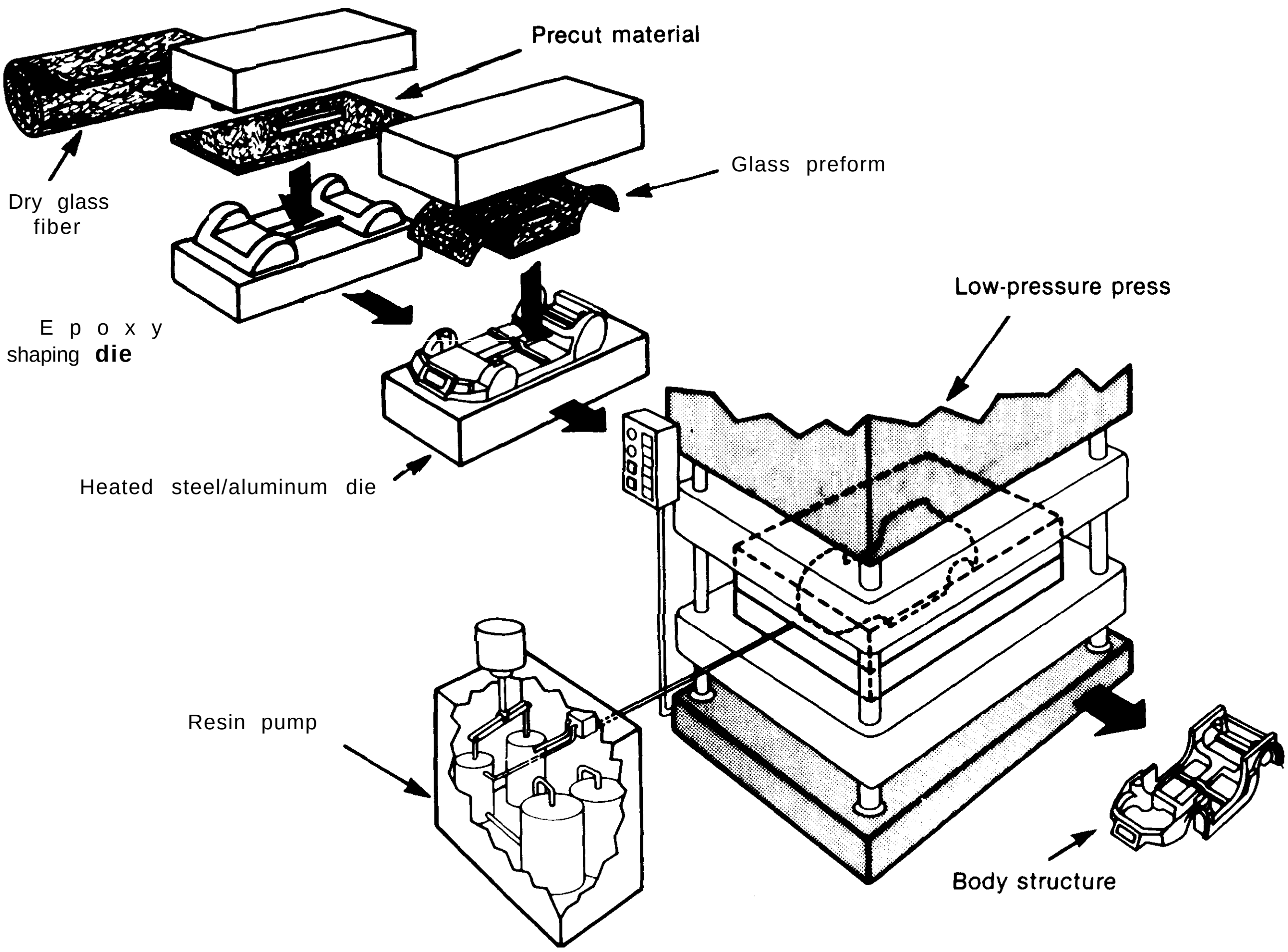
The basic concepts required for this process are practiced fairly widely today in the boat-building and specialty-auto business. However, with few exceptions, the glass preform is hand-constructed and the resin injection and cure times are of the order of tens of minutes or greater. Also, dimensional consistency necessary for assembling high-quality products has not been studied for this process.

Major reductions in manufacturing time and automation of all phases of the process are necessary to increase automotive production rates. However, the basic ingredients of precise fiber control and highly integrated complex part geometries (including, for instance, box sections) are an integral part of this process and offer potentially large cost benefits.

There are two basic elements associated with the high-speed resin transfer molding (HSRTM) process that must be developed. The assemblage of the glass preform must be developed such that it can be placed in the mold as a single piece. In addition, the introduction of the resin into the mold must be rapid and the cure cycle must be equally fast to provide a mold-closed/mold-open cycle time of only a few minutes, A schematic of the process is presented in figure 7-17.

There are two processes currently in use that may have the potential to offer rapid resin injection and cure times. One is resin transfer molding. Currently in widespread use at slow rates,

Figure 7-17.–High-Speed Resin Transfer Molding (HSRTM)



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor-Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

it could be accelerated dramatically by the use of low-viscosity resins, multiport injection sites, computer-controlled feedback injection controls, and sophisticated heated steel tools. There do not appear to be any significant technological barriers to these kinds of developments, but it will require a strong financial commitment to prove out such a system. A schematic of the process is presented in figure 7-18, which also illustrates a variant on the process usually termed squeeze molding.

The second process that promises rapid injection and cure cycles is reaction injection molding (RIM). In reaction injection molding, two chemicals are mixed and injected simultaneously; during injection the chemicals react to form a thermosetting resin. Once the dry glass preform is in the mold, the resin can be introduced by any appropriate procedure, and reaction injection would be ideal, provided the resultant resin has adequate mechanical properties. The inherent low viscosity of RIM resins would be ideal for rapid introduction into the mold.

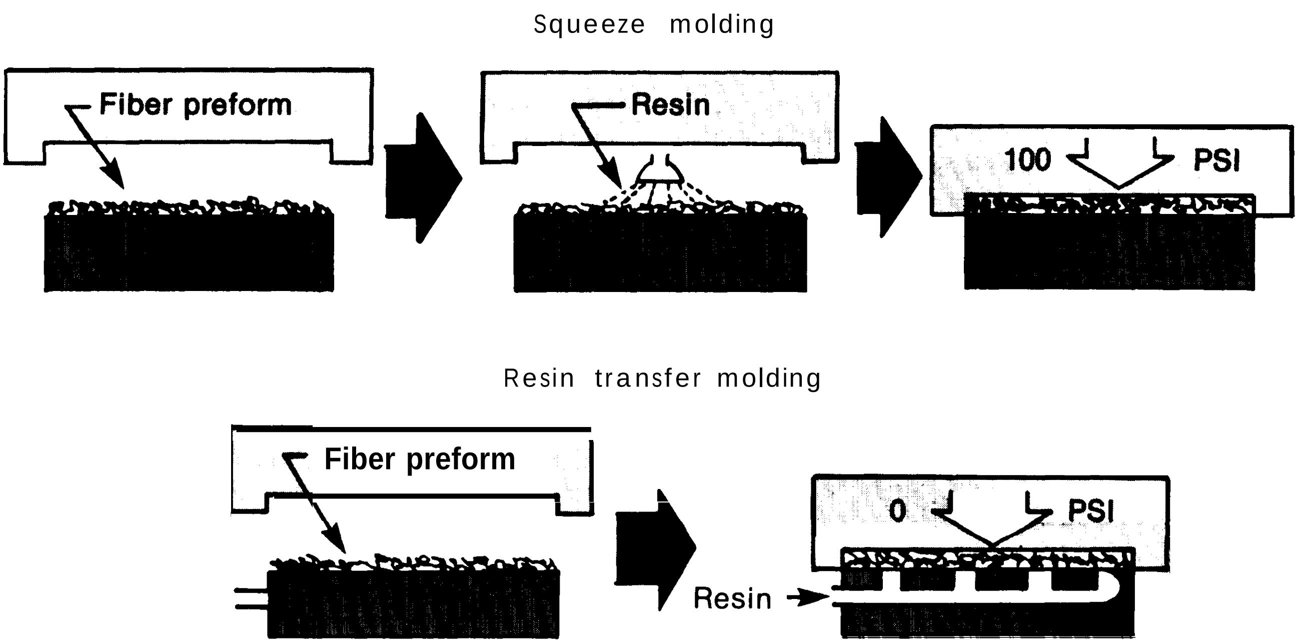
Full three-dimensional geometries including box sections, are attainable by preform molding. In addition, only low-pressure presses are necessary. The high degree of part integration maximizes effective stiffness and minimizes assembly.

In principle, major portions of vehicles could be molded in one piece; for instance, Lotus auto body structures consist of two major pieces (albeit molded very slowly) with one circumferential bond. If similar-size complex pieces could be molded in minutes, a viable volume production technique could result.

Filament Winding

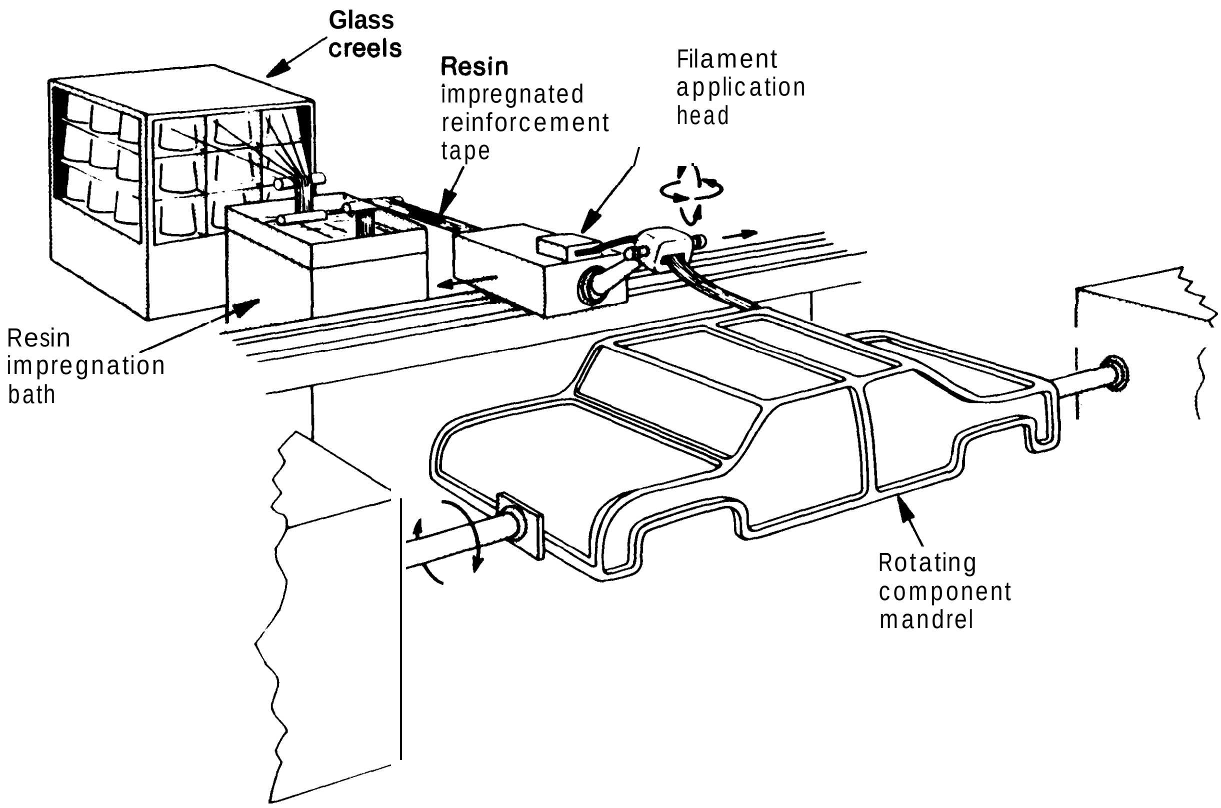
Filament winding is a PMC fabrication process that for some geometric shapes can bridge the gap between slow, labor-intensive aerospace fabrication techniques and the rapid, automated fabrication processes needed for automotive manufacturing. The basic process uses a continuous fiber reinforcement to form a shape by winding over some predetermined path. Figure 7-19 provides a process schematic.

Figure 7-18.—Squeeze Molding and Resin Transfer Molding



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7.19.—Filament Winding Process



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

The complexity and accuracy of the winding path are highly controllable with microcomputer-controlled winding machines. Thin, hollow shapes having high fiber-to-resin ratios are possible, thereby making the process well suited to lightweight, high-performance components. Glass fiber, aramid, or carbon fiber can be used as the winding material. Filament winding can use either thermosetting or thermoplastic resin systems.

The uniform fiber alignment afforded by the process provides high reliability and repeatability in filament-wound components. Some simple shapes, such as leaf springs, can be fabricated by this process and are currently in production on a limited basis.

Thermoset Filament Winding

The majority of filament winding done today uses thermosetting resin systems. In the thermoset filament-winding process, the resin and reinforcement fibers are combined (referred to as wetting out of the reinforcement) immediately prior to the winding of the fibers onto the part. The wetting-out and winding processes require precise control of several variables. Reinforcement tension, resin properties, and the fiber/resin ratio all relate directly to the final physical properties of the part. As the winding speed and part complexity increase, these variables become increasingly difficult to control.

Winding of complex parts at automotive production rates will require major process developments. The likely potential of thermoset filament winding in automotive applications is in the fabrication of simple shapes such as leaf springs, in which the cost penalty involved due to slow production speeds can be offset by a need for high reliability and maximum use of material properties.

Thermoplastic Filament Winding

Filament winding of thermoplastic materials represents both the leading edge of this technology and the area in which its potential benefit to the automotive industry is greatest.

Thermoplastic filament winding uses a reinforcement preimpregnated with a thermoplastic resin rather than a reinforcement impregnated with a thermosetting resin at the time of winding. The preimpregnated filament or, more often, tape, is wound into the appropriate shape in a manner similar to the thermosetting filament-winding process, with the exception of a local heating and compaction step.

The reinforcement tape is heated with hot air or laser energy as it first touches the mandrel. The heat melts the thermoplastic matrix both on the tape and locally on the substrate permitting a slight pressure applied by a following roller to consolidate the material in the heated area. Because the reinforcement filament is already wet out in a prepregging process, the substrate is solidified over its entirety with the exception of a small zone of molten material in the area of consolidation.

The limitations with respect to filament tension, filament wet-out, and speed at which a wet filament can be pulled through a payout eye are no longer a major concern with thermoplastic filament winding. Thick sections can be rapidly wound, and nongeodesic and concave sections can be formed. However, the applicability to geometries as complex as body structures is not established. Currently, problem areas exist in the carryover of physical properties due to the limited amount of research that has been done on the process. There are problems with the control of the heating and consolidation of the thermoplastic materials that yield less than predicted values for tensile strength and interlaminar shear strength.

Although the thermoplastic materials will likely expand the structural component applications in which thermoplastic filament winding can economically compete with thermoset filament winding, the increased speed and shape capabilities will not entirely offset the limited degree of part integration possible. The inability to integrate box sections with large flat panels in a one-piece structure having complex geometry will tend to limit the penetration of filament winding in body structures.

IMPACT ON PRODUCTION METHODS

The following sections discuss the various impacts of these candidate technologies on automobile production methods.

Manufacturing Approach

The manufacturing approach for producing autos with PMC structural parts will be considerably different from the methods employed for building conventional vehicles with steel bodies. Currently, many domestic automotive assembly plants for steel vehicles are used for very little basic manufacturing. Instead, high-volume sheet steel stamping plants, geographically located to service several assembly plants, produce body components and small assemblies and ship them to the assembly plants. The plants assemble the sheet metal components into an auto body structure as presented in table 7-4 and figure 7-20a and b.

An auto body is a complex structure, and its design is influenced by many demanding factors. At the present time, it appears that two systems can be considered as possible processes to build the structural panels for PMC auto bodies.

One system consists of compression molding. Compression molded thin-walled panels are first bonded together to form structural panels (see figure 7-21) and then the structural panels, are assembled to form auto bodies. The other system involves HSRTM, in which preforms of fiber reinforcement are combined with foam cores, placed in a mold, and resin-injected to form large, three-dimensional structural panels (see figure 7-22). These panels are then assembled into auto bodies. It is important to note that the filament-winding process is viewed as a limited construction method largely due to the restricted complexity that is available with this technique.

Table 7-4.—Typical Body Construction System: Steel Panels

- Build front structure—assemble aprons, radiator support, torque boxes, etc. to dash panel
- Build front floor pan assembly
- Assemble front and rear floor pan into underbody assembly
- Complete spot welding of underbody assembly
- Transfer underbody to skid
- Build left-hand and right-hand bodyside assemblies
- Move underbody, bodyside assemblies, cowl top, windshield header, rear header, etc. into body buck line and tack-weld parts
- Complete spot welding of body
- Braze and fusion-weld sheet metal where required
- Assemble, tack-weld and respot roof panel to body
- Assemble front fenders to body
- Assemble closure panels (doors, hood, decklid) to body
- Finish exterior surface where required

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

Therefore, it cannot now be considered as a competitive process for high-volume body structure fabrication.

Compression Molded Structural Bodies

Compression molded structural panels might be produced as presented in table 7-5 and figure 7-21. Panel assemblies (side panels, floor pans, roof panels, etc.) are produced from inner and outer components. First, SMC sheet must be manufactured and blanks of proper size and weight arranged in a large predetermined pattern on the die surface. The panels are then molded in high-tonnage presses. After molding, the parts are processed in a number of secondary operations, bonded together, and transported to the body assembly line.

Body construction commences with the floor panel being placed in an assembly fixture. Side panel assemblies and mating components are bonded in place. Attachment points for the exterior body panels are drilled and the body structure is painted prior to transporting to the trim operations. (The body construction sequence is described later, see table 7-9 and figure 7-24.)

High-Speed Resin Transfer Molded Structural Bodies

HSRTM processing consists of three stages that involve making a dry glass fiber preform, combining the preform with foam cores, and injecting resin into the mold to infiltrate the preform.

First, dry glass preform reinforcements must be fabricated. The preform may be composed of primarily randomly oriented glass fibers with added directional glass fibers or woven glass cloth for

Figure 7-20(a).-Typical Assembly of Steel Underbody

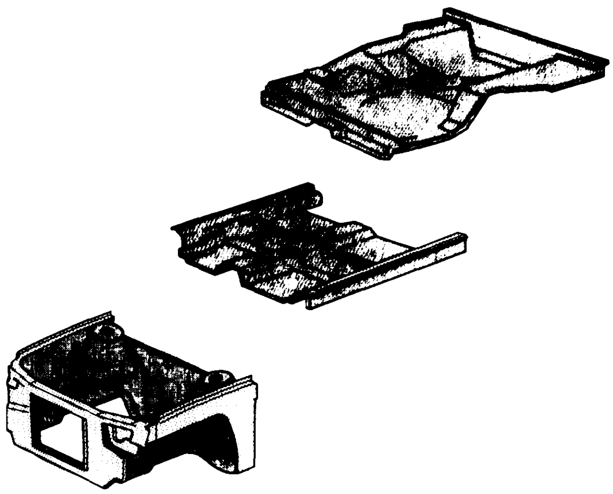
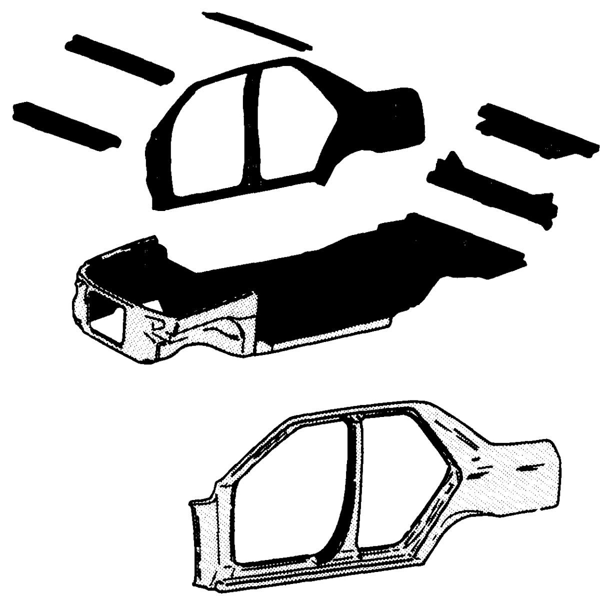
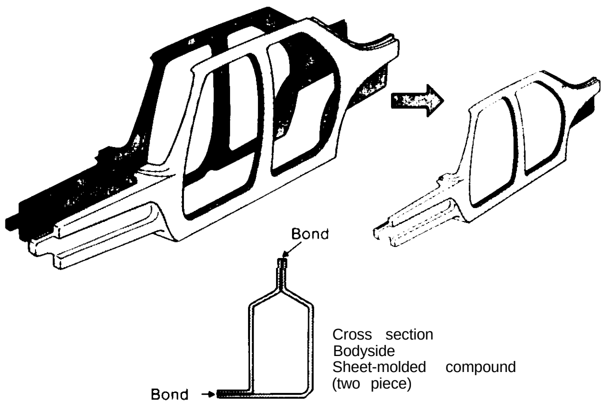


Figure 7=20(b). -Typical Assembly of Underbody, Bodyside Assemblies, Etc. into the Completed Steel Body Shell



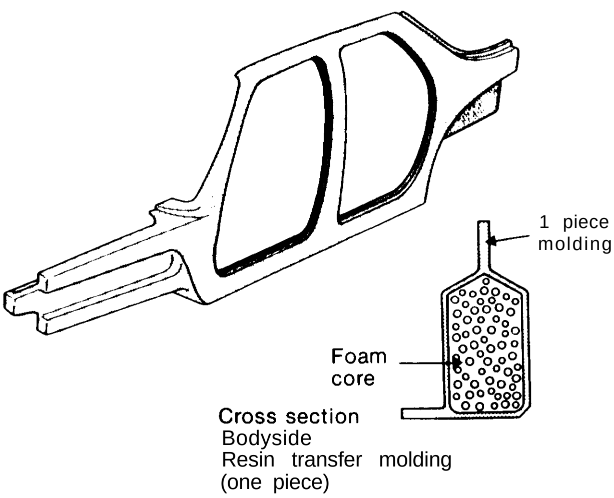
SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure)" contractor report for OTA, 1907.

Figure 7-21.—Typical Assembly of Composite Bodyside Panel by Adhesive Bonding of Inner and Outer SMC Molded Panels



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-22.—Typical One. Piece Composite Bodyside Panel With Foam Core Molded by High-Speed Resin Transfer Molding



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

local reinforcement of high-stress areas. To be economically viable, preform fabrication must be accomplished by a highly automated technique. The process sequence is described in table 7-6.

Second, foam core reinforcements must be fabricated to obtain three-dimensional inserts, such as those used in rockers and pillars. Local

Table 7-5.—Compression Molded Structural Panels

- Fabricate and prepare SMC charge
- Load charge into die and mold panel
- Remove components from molding machine (inner and outer panels), trim and drill parts as required
- Attach reinforcements, latches, etc., to inner and outer panels, with adhesive/rivets
- Apply mixed, two component adhesive to outer panel
- Assemble inner and outer panels, clamp and cure
- Remove excess adhesive
- Remove body panel from fixture and transport to body construction line'

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987.

Table 7-6.—Preform Fabrication Sequence

- Apply random glass fibers over mandrel
- Apply directional fibers (or woven cloth) for local reinforcement
- Stabilize preform
- Remove preform and transfer to trim station
- Trim excess fibers
- Transfer to HSRTM panel molding line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure, " contractor report for OTA, 1987,

metal reinforcements and fasteners can be prepositioned in the mold at this point during foam fabrication. The chemicals are subsequently introduced into the mold and the resulting reaction yields an accurately shaped foam part. The process sequence is described in table 7-7.

Third, the body structural panel is molded. A gel coat may be sprayed in both the lower and upper mold cavities to obtain a smoother surface on the finished part. Preforms, foam cores, and any necessary additional local reinforcements and fasteners are placed in the respective lower and upper mold cavities. In high production,

Table 7.7.—Foam Core Fabrication Sequence

- Clean mold and apply part release
- Install reinforcements and basic fasteners
- Close mold
- Mix resins and inject into mold
- Chemicals react to form part
- Open mold
- Unload part and place on trim fixture
- Trim and drill excess material
- Transport to HSRTM body panel line

SOURCE; P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

these operations must be carried out robotically. The mold is closed and a vacuum may be applied. The resin is injected, infiltrates the preform, and cures to form the body structural panel. The molding is then removed from the die and trimmed. This process sequence is described in table 7-8 and illustrated in figure 7-22.

The final stage of body construction is the assembly of the individual panels, The underbody panel is placed on the body construction line. Adhesive is applied to the side panels by robots in the appropriate joint locations, the side panels are mated to the underbody and clamped in place, and the fasteners are added, Similarly, the remainder of the body structure is located and bonded to form a complete auto body. After curing, the body is washed and dried, prior to transfer to trim operations. This process sequence is described in table 7-9 and illustrated in figure 7-23.

(Note that the body assembly sequence given in table 7-9 is essentially common to both compression molding and HSRTM. This is only one illustration of the assembly of a number of moldings to form the body—the number of moldings could vary from 2 to 10 depending on the specific design and manufacturing details,[19])

[19] Beardmore, Johnson, and Strosberg, op. cit., footnote 1.

Table 7-8.—HSRTM Molded Structural Panels

- Clean mold and apply part release
- Spray gel coat into mold (optional)
- Insert lower preforms and local woven fiber reinforcements
- Insert specialized reinforcements and fasteners
- Insert foam cores
- Insert upper preforms and local woven fiber reinforcements
- Close mold
- Apply vacuum to mold (optional)
- Inject resin and allow chemicals to react
- Open mold
- Remove assembly and place in trim fixture
- Trim and drill body panel
- Transport to body assembly line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co.. "impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7.9.—Body Construction Assembly Sequence

- Place underbody in body build line
- Apply adhesive to bond lines of side panels and cowl
- Mate side panels to underbody, clamp and insert fasteners
- Apply adhesive to cowl top assembly, lower back panel and mate
- Apply adhesive to roof panel and mate to body side panels
- Transfer body to final trim operations
- After final trim, the painted exterior body panels are assembled to the auto body

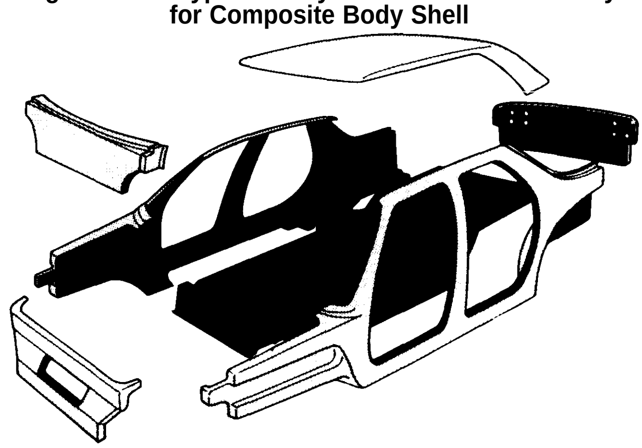
SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

As noted, figure 7-23 is a schematic of a multipiece PMC body. For comparison, a two-piece HSRTM body construction is illustrated in figure 7-24 to indicate the various levels of part integration that might be achieved using PMCs. In both these scenarios, the body shell would consist of PMC structure with no metal parts except for molded-in steel reinforcements.

Assembly Operation Impact

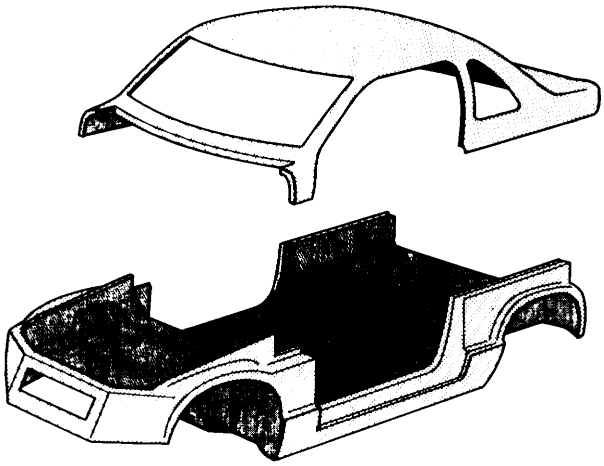
In both the compression molding and HSRTM scenarios, there would be a considerable change

Figure 7.23.–Typical Body Construction Assembly for Composite Body Shell



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-24.–Typical Body Construction Assembly Using Two Major Composite Moldings



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure," contractor report for OTA, 1987,

Table 7-10.—Effect of Composites on Body Complexity

Vehicle design and material	Typical number of major parts in body structure	Typical number of assembly robots
A. Conventional welded steel body structure. . . . .,	250 to 350	300
B. Molded SMC body structure.	10 to 30	100
C. High-speed resin transfer molded composite/body structure	2 to 10	50
Estimated part reduction (A less B)	240 to 320	200 to 250
Estimated part reduction (A less C) ,,, ...	248 to 340	250 to 280

SOURCE P Beardmore, C F Johnson, and G G Strosberg, Ford Motor Co , "Impact of New Materials on Basic Manufacturing Industries, A Case Study Composite Automobile Structure, contractor report for OTA, 1987

in the assembly operations for PMC vehicles versus conventional steel vehicles. The number of component parts in a typical body structure (body-in-white less hoods, doors, and decklids) varies with vehicle design and material, as presented in table 7-IO.

The dramatic reduction in the number of parts to be assembled in a PMC vehicle would result in a corresponding reduction in the number of subassembly operations and amount of subassembly equipment, as well as a reduction in the required floorspace. For instance, robots used to produce PMC assemblies can lay down an adhesive bead considerably faster than robots can spotweld a comparable distance on mating components. Therefore, it is anticipated that there would be a considerable reduction in the number of robots and complex welding fixtures required.

Labor Impact

The design and engineering skills that would be required to apply PMCs would be somewhat different from the skills used for current metal applications. A broader materials training curriculum would be required because the chemical, physical, and mechanical properties of PMCs differ significantly from those of metals. These programs are currently being developed at some universities but significant expansion would be necessary to ensure this trend on a broader scale.

The overall labor content for producing a PMC body would similarly be reduced as numerous operations would be eliminated. However, it is important to note that body assembly is not a labor-intensive segment of total assembly. Other assembly operations that are more labor-intensive (e.g., trim) would not be significantly affected, Thus, the overall labor decrease due to PMCs might be relatively small.

The level of skills involved in PMC assembly line operations (e.g., bonding operations) is not expected to be any more demanding than the skill level currently required for spotwelding conventional body assemblies. In either case, good product design practice dictates that product assembly skill requirements be matched with the skill levels of the available workers to obtain a consistently high-quality level.

IMPACT ON SUPPORT INDUSTRIES

The increased use of polymer composites could strongly affect the existing automotive support industries as well as promote the development of new ones.

Material Suppliers, Molders, and Fabricators

PMC vehicle body structures of the future, whether built with compression-molded or HSRTM parts, are expected to be designed with components integrated into modular subassemblies. Therefore, these units will be of considerable size and are not conducive to long-range shipping. Manufacturing on site in a dedicated plant for molding body construction and assembly operations, just prior to trim and final assembly of the vehicle, will become necessary.

PMC automobile production, in relatively high volumes, will require additional qualified supplier capacity. The extent of these requirements will be dependent on the economic attractiveness and incentives for developing in-house capacity by the automotive manufacturers. Fortunately, these demands are likely to be evolutionary, in that the automotive industry would undoubtedly commence with low annual volume (10,000 to 60,000) PMC body production units.[20] When (and if) higher volume production of PMC bodies is planned, additional supplier capacity can be put in place as a result of supplier/manufacturer cooperation throughout the normal lead time (4 to 6 years) for the planning, design, and release of a new vehicle to manufacturing.[21]

Although compression molding is the most mature of the evolving PMC production techniques, a major conversion to SMC for body structures would require a substantial increase in resin and reinforcement output, mold-building capacity, molding machine construction, component molding, subassembly facilities, adhesives, and quality control tools, etc.

If the HSRTM processing concept is used, resin and reinforcement suppliers would need to substantially expand their output (as in the case of compression molding) and perhaps develop new products to meet the unique demands of the process. Tooling is similar in construction to that used in injection molding, and therefore manufacturers of this type of tooling would likely expand to fill the need. If inexpensive electroformed molds, which consist of 0.25 inch of electroplated nickel facing on a filled epoxy backing (used today for low-pressure or vacuum-assisted molding) become feasible, this phase of the industry would have to be developed and expanded. Because molding pressures for this process are low, high-tonnage hydraulic presses would not be needed. However, companies specializing in automation and resin handling equipment would play an increased role.

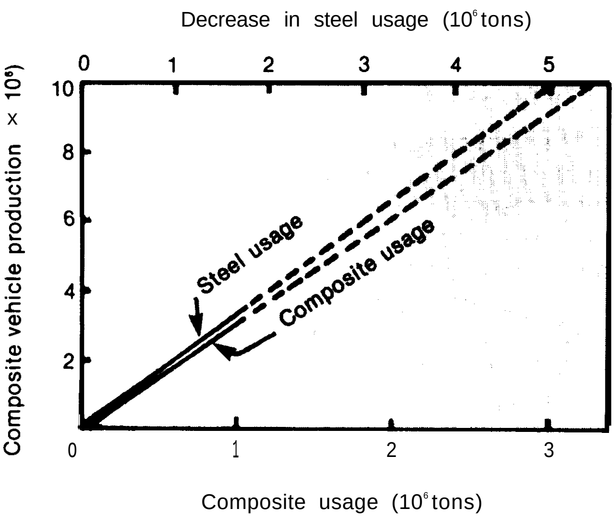
If PMC structures were suddenly implemented, there would bean expected shortfall of qualified molders and fabricators regardless of the process chosen. It is more likely, however, that implementation would be evolutionary, and the supply base would be addressed during the PMC vehicle planning and design stage. To enlarge the supply base, the auto industry is currently working with, and encouraging, qualified vendors to expand and/or diversify, as required, to support product plans. Additionally, with growth in PMC demand, new suppliers would be expected to become qualified.

Current suppliers may also form joint ventures and/or make acquisitions to expand capabilities during the phase-in period of PMC structures. Along with the need to expand materials supply and facilities, there is the significant need to develop and retrain qualified personnel to provide support for both supplier and automotive industry operations.

The current molding capacity for SMC devoted to the automotive industry is of the order of 500 million to 750 million pounds annually.[22] Figure 7-25 projects the additional volume of PMCs that would be needed as a function of producing a high volume of autos with a high content of composites. The data are based on a substitution for

[20] Ibid.
[21] Ibid.
[22] Ibid.

Figure 7-25.—Effect of Composite Use on Steel Use in Automobiles



Increase in composites usage and associated decrease in steel usage for various production volumes of composite-intensive vehicles. Assumes 1,000 lb. of steel is replaced by 650 lb. of composites in a typical vehicle weighing 2,700 lb. that contains 1,600 lb. of steel.
Two million composite-intensive vehicles per year causes a loss of one million tons of steel, which is roughly 12 percent of steel usage in automobiles, see table 7-11.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

a typical vehicle weighing 2,700 pounds and containing 1,600 pounds of steel. Of this 1,600 pounds of steel, 1,000 pounds of steel have been replaced by 650 pounds of PMCs. It is evident that there would be a relatively massive incremental amount of PMCs needed for even 1 million vehicles per year–about 300,000 tons (650 million pounds); i.e., roughly a doubling of current SMC capacity.[23] Each additional million vehicles would require the same increase, creating (ultimately) an enormous new industry.

Steel Industry

The implementation of PMCs in automobiles would clearly have an impact on the steel industry. As with the plastics industry, this impact would be volume-dependent. In the initial stages, with volumes in the range of 10,000 to 60,000 vehicles per year, there would be only a minimal effect-a small loss in steel tonnage, some excess press capacity, and some additional stamping die building capacity.[24] The loss of steel tonnage from the steel mills would cause additional problems for this already beleaguered segment of industry. Both captive and/or supplier stamping plants would have idle capacity. Stamping die builders would lose orders, unless they could also build molds for plastics. However, these potential problems for the steel industry would be evolutionary and would take several years to occur after the successful introduction of vehicles using this technology.

Figure 7-25 can be used to place this potential impact in perspective. The decrease in steel use as a function of increasing production volume of cars with a high PMC content would become significant only at intermediate volume levels. The data reproduced in table 7-11 show that at volumes of up to 500,000 PMC vehicles per year, automotive use of steel would drop only about 250,000 tons (or 3 percent) per year.[25] Since motor vehicle manufacturing uses about 15 percent of all steel consumption in the U.S.,[26] steel consumption would drop 0.45 percent for volumes of 500,000 PMC vehicles per year. Major steel production decreases would result only from a major change in PMC vehicle volume—e.g., 2 million vehicles or more.[27]

[23] 1 bid.

[24] Ibid.

[25] If a vehicle is specifically designed for PMCs instead of steel, and, for instance, the volume is on the order of *500,000* units, the impact would be greater.

[26] U.S. Department of Commerce, Bureau of Economic Analysis, *The Detailed Input-Output Structure of the U.S. Economy, 1977,* vol. 1, Washington, DC, 1984.

[27] Beardmore, Johnson, and Strosberg, op. cit.

Table 7-11.—Automotive Steel Usage (based on annual volume of 10⁷ vehicles)

Production volume of composite-intensive vehicles	Steel usage (10⁶) tons
0	8
50,000	7.975
500,000	7.75
5,000,000	5.5
10,000,000	3.0

SOURCE: P. Beardmore, C.F, Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

It is also recognized that the steel industry and its suppliers are aggressively seeking methods to reduce costs and provide a wider range of steels. This healthy economic competition between steel and PMCs will have an effect on the timing of PMC auto introductions and the volumes to be produced. World competition in the steel industry is leading to the availability of a wider range of high-strength steels with improved quality, resulting in an increase in productivity for the end user. The balance between improved economic factors for steel use and the rate of improvement of PMCs processing will dictate the use, rate of growth, and timing of the introduction of PMC vehicles.

Repair Service Requirements

Another support industry of importance is the PMC repair service required to repair vehicle damage caused in accidents, etc. During the design process, automobile engineers will design components and body parts to simplify field repairs. For repair of major damage, large replacement components or modules will have to be supplied. At the present time, the comparative expense of repairing PMC structures relative to steel is unclear. Replacement parts or sections will tend to be more expensive. However, low-energy collisions are expected to result in less damage to the vehicle. Thus, the overall repair costs across a broad spectrum of vehicles and damage levels are not anticipated to be any higher than current levels.

Exterior SMC body panel repair procedures are already in existence at automotive dealerships and independent repair shops specializing in fiberglass repairs. With additional PMC use, it is expected that the number of these repair service facilities will increase. To repair the PMC structure, dealers and independent repair centers will need new repair procedures and repair materials. The development of the appropriate repair procedures will be contained well within the time frame of PMC vehicle introduction. There will be new business opportunities to establish additional independent shops.

As with any new vehicle design, PMC repair procedures must be fully developed and standardized, along with the additional training of repair personnel. This training will require skill levels equivalent to those required for steel repair.

PMC Vehicle/Component Recycling

The recycling industry is another support industry that will undergo significant change in the longer term if PMC vehicles become a significant portion of the volume of scrapped vehicles. Current steel vehicle recycling techniques (shredders and magnetic separators) will not be applicable, and cost-effective recycling methods will need to be developed exclusively for PMCs. Low volumes of scrap PMC vehicles will have minimal effect, but the problems will increase as the volume reaches a significant level. This level is estimated to be in the range of 20 percent or more of the total vehicles to be salvaged .28

Plastics must be segregated into types prior to recycling. Currently, only clean, unreinforced thermoplastic materials can readily be reclaimed, but the techniques are somewhat inadequate and tend to be very expensive. Fortunately, the calorific value of many thermoplastics approaches that of fuel oil. Some waste-incinerating plants now operate with various types of plastics as fuel. One developing use for plastic waste involves pulverizing plastics and using their calorific value as a partial substitute for fuel oil in cement kilns. Some plastics in automobiles can be recycled by melt recovery, pyrolysis, and hydrolysis, but cost-effective methods are not yet in place.

Thermoset plastic components, such as SMC panels and other PMC body components, currently cannot easily be reclaimed because of their relatively infusible state and low resin content. Grinding, followed by reuse in less demanding applications such as roadfill or building materials, is possible, but is not currently economical. Consequently, these kinds of parts are used as landfill or are incinerated. Again, at low volumes, these recycling procedures are acceptable, but they would not be viable at high scrap rates.

Without the advent of some unforeseen recycling procedures, it appears likely that incineration will have to be the major process for the fu-

*81 bid.

ture. The viability of incineration will either have to be improved by more efficient techniques for more favorable economics or some penalty will likely have to be absorbed by the product.

POTENTIAL EFFECTS OF GOVERNMENTAL REGULATIONS

Any major potential changes in automotive industrial practice, such as the large-scale substitution of a new structural material, must take into consideration not only current regulations but also future regulations that may already be under consideration or that may be initiated be*cause* of the potential changes in industrial practice. One example is the increased safety (crash-resistance) requirements already under active consideration. Another is the potential increases in CAFE standards for the 1990s. Although the following discussion of such potential regulations is not comprehensive, it serves to illustrate the importance of such considerations in introducing major materials changes to the automotive industry.

Health Safeguards

The introduction of fiber-reinforced plastics in significant volumes into the automotive workplace may raise health and environment concerns. Any fibers in very fine form have the potential to create lung and skin problems, and although glass fibers may be among the more inert types of fiber, there must still be adequate precautions taken in handling these fibers.

Currently, glass fibers are widely used in various industries such as molding industries, boat building, and home construction; extension to the automotive industry would probably not require development of safeguards other than those used within those existing industries.

However, the widespread nature of the automotive business would undoubtedly raise awareness of potential health risks and could precipitate more stringent requirements for the workplace. Although such additional precautions may not pose a technological problem, the extent of the regulations could have a significant effect on the economic viability of the use of composites.

Similarly, the same problems could arise with the resin matrix materials of these PMCs. It is not clear which specific resin materials will be dominant for PMCs use, but there is a widespread concern regarding all chemicals in the workplace and in the environment.

There are already strong regulations concerning chemical use and handling, but again, the sheer magnitude of the automotive industry is likely to bring such requirements to the forefront of interest and may result in additional legislation. This could result in limitation of the types of resins used and implementation of additional safeguards. The impact is less likely to prevent implementation of PMCs technology than it is to affect the economic viability and timing of the introduction of this technology.

Recyclability

The current recycling of scrap automobiles is a major industry. Sophisticated techniques have been developed for separating the various materials, and cost-effective recycling procedures are an integral part of the total automotive scene. Because steel constitutes 60 percent (by weight) of a current automobile, the recycling of steel is the major portion of the recycling industry. Recycling of PMCs is a radically different proposition, and use of these materials will necessitate development of new industrial recycling processes if large volumes are manufactured.

If PMCs are only applied in low-volume specialty vehicles, however, current recycling techniques of landfill and incineration will probably be adequate.

The potential for large numbers of composite-intensive vehicles to be scrapped will undoubtedly raise the issue of disposal to the national spotlight. One concern is that there would be a disposal problem due to a lack of economic incentives to recycle. Consequently, this problem may need to be addressed by legislation before widespread use of these materials is permitted. The result of such legislation could be the commitment of resources at an early stage of development with payback as part of the. overall cost of PMC development.

Crash Regulations

There are regulations in existence, and others proposed, that set or would set impact-survival criteria in frontal impacts, side crash tests, and vehicle-to-vehicle impacts. Various scenarios have been proposed for making these standards more stringent (e.g., raising frontal-impact criteria from 30 to 35 miles per hour, and possibly higher).

Basic experience to date in crash-energy management has primarily been with steel vehicles and, consequently, the specific wording of the regulations is based on the characteristics of these vehicles. Vehicles consisting largely of PMC materials absorb energy by significantly different mechanisms, and the details of impact would be very different from those of steel vehicles, even though the objective of occupant protection would be the same.

Thus, new regulations in this area could contain provisions that would preclude the use of PMCs because of the lack of information. For instance, if a requirement were promulgated that stated no fracture of a major body structure shall occur during a certain impact, PMCs would be excluded because, unlike steels, internal fracture of the PMCs is a critical part of energy absorption. Thus, detailed wording of crash regulations based on steel experience could inadvertently jeopardize the potential use of PMC structural materials.

Fuel Economy Standards

Just as some regulations might produce deterrents to PMCs use, others might promote development and use. If CAFE requirements were drastically increased, there would be a limited number of options for increasing fuel efficiency-downsizing, increased power train efficiency, and weight reduction. In terms of weight reduction, aluminum alloys and PMCs would represent perhaps the major options. Thus, legislation requiring a marked increase in fuel economy might tend to promote the development and use of PMCs, providing that functional requirements, manufacturing feasibility, and overall economic factors are proven.

TECHNOLOGY DEVELOPMENT AREAS

Although years of development efforts have advanced structural composites so that they constitute a significant material for use in the aviation and aerospace industries, the cost-effective use of these materials in the automotive industry requires considerable additional developmental work in the following areas.

Compression Molding

Improvements in SMC technology are required in the areas of reduced cycle times, reproducibility of physical properties and material handleability. A major improvement would be a significant reduction in manufacturing cycle time. Current objectives are to cut the conventional time from 2 to 3 minutes to 1 minute or less. Development of materials requiring less flow to achieve optimum physical properties would permit more reproducible moldings to be made. Other potential technology improvements for SMC include a reduction in the aging time for material prior to molding, an internal mold release in the material, an improved cutting operation to prepare a loading charge for the molding machine, automated loading and unloading of molding machines, and improved dimensional control of final parts.

High-Speed Resin Transfer Molding

There are two critical segments of this process that require major developments to achieve viability. One is reduction in manufacturing cycle time, and new, faster curing resins currently under development should make significant contributions in this area. The other is development of automated preform technology (foam core development and subassembly), which is critical to achieving cost-effectiveness. This is perhaps the area requiring major innovation and invention, but it has yet to be perceived by the existing fiber and fiber-manipulation industry to be a major area for development.

Fiber Technology

There are three major areas in fiber technology that must be optimized to promote fiber use in high-production industries: 1) improved physical properties of the composite, 2) improved fiber handling and placement techniques, and 3) improved high-volume production techniques providing fibers at lower cost. Superior physical properties would result from improved sizings (fiber coatings) to reduce fiber damage during processing and provide improved mechanical properties in the finished components. Fiber-handling equipment permitting high-speed, precise fiber placement with minimal effect on fiber properties is a vital requirement for the development of stable, three-dimensional preforms. Cost minimization is a critical factor in using glass fibers but also should be considered from the viewpoint of generating other fibers (e.g., carbon fibers) at costs amenable to mass-production use.

Joining

Two key areas dominate the category of joining technology. First, adhesives and mechanical fasteners must be tailored for PMC construction, to develop the necessary combination of production rate and mechanical reliability. Second, there is a need for the development of design criteria and design methodologies for adhesive joints. Neither of these areas have been systemically developed for a mass-production industry and far greater attention must be paid to joining materials and to methods for alleviating any problems in this element of the overall PMCs technology.

General Technology Requirements

Design methodologies for use with PMCs to cover all aspects of vehicle requirements must be developed to a degree comparable to current steel knowledge. The ability to tailor PMCs for specific requirements must be integrated into such design guides, and this makes the task more complex than the equivalent guidelines for isotropic materials (e.g., metals). Manufacturing knowledge and experience, which provide constraints for the design process, must be fully documented to optimize product quality, reliability, and cost-effectiveness, The degree of component integration must be a key factor in determining manufacturing rates, and this interdependence of design and manufacturing will evolve only over a protracted time period. This buildup of experience will be the key factor in resolving overall economic factors for the production of composite vehicles.

Standards

The complexity of PMC materials relative to metals will require the development of standard testing procedures and material specifications as is discussed in chapter 5. The rapid proliferation of materials in the PMC arena will not permit final establishment of these generic standards until PMC technology matures. It is likely that specific corporate standards will be used in the interim prior to professional society actions.

SUMMARY

The extension of PMCs use to automotive structures will require an expanded knowledge of the design parameters for these materials, together with major innovations in fabrication technologies. There is abundant laboratory evidence and some limited vehicle evidence that strongly indicates that glass fiber-reinforced PMCs are capable of meeting the functional requirements of the most highly loaded automotive structures. There are, however, sufficient uncertainties (e.g., long-term environmental effects, complex crash behavior) that applications will be developed slowly until adequate confidence is gained. Nevertheless, it seems inevitable that the functional questions will be answered, and it only remains to be seen how soon.

perhaps the most imperative requirement is the cost-effective development of fabrication techniques. There will be a prerequisite to widespread use of PMCs in automotive structures. High-volume, less-stringent performance components can be manufactured by variations of compression molding techniques. it is the high-volume, high-performance manufacturing technology that needs development, and the HSRTM process appears to be a sleeping fabrication giant with the potential of developing into just such a process.

All the elements for resolving the rapid, high-performance issue are scattered around the somewhat fragmented PMCs industry. It will require the appropriate combination of fiber manufacturers, resin technologists, fabrication specialists, and industrial end users to encourage the necessary developments.

The advent of composite-intensive vehicles will be evolutionary. The most likely scenario would be pilot programs of large PMC substructures as initial developments to evaluate these materials realistically in field experience. This would be followed by low annual production volumes (20,000 to 60,000 units) of a composite-intensive vehicle that would achieve the extensive manufacturing experience vital to the determination of realistic fabrication guidelines and true economics.[29] The data derived from such introduction would determine the potential for high-volume production.

Currently, the industry infrastructure is not in place for PMC-intensive vehicles. In addition, the supply base could presently respond to only low-volume production of PMC vehicles. Neither of these situations is a major restriction in that the anticipated long development time would permit the appropriate changes to occur over a protracted period. Rather, the initial decisions to make the necessary changes and (substantial) financial commitments will have to be based on significant evidence that PMC vehicles are viable economically and will offer customer benefits.

irrespective of the scenario for the eventual introduction of PMC vehicles, there are probably some general conclusions that can be drawn relative to the impact of these materials. PMC applications are unlikely to have a large effect on the size of the labor force because the major changes are not in labor-intensive areas of vehicle manufacture and assembly. Likewise, the necessary skill levels for both the fabrication of the PMC parts and assembly of the body should not be significantly changed. Engineering know-how would be very different, but the needed skill levels would be similar to those already in place.

Perhaps the largest effect would be on the supply industries, which would need to implement production of PMCs. This would involve both a change in technology for many current suppliers, together with the development of a new supply base. The steel industry would experience a corresponding decrease in output, but the decrease would only be of major proportion if PMC vehicles became a significant proportion of total vehicle output. The repair and recycling industries would similarly undergo a major change to accommodate the radical change in the vehicle materials.

29 Ibid ,