

# Research Trends in Polymer Materials for Use in Lightweight Vehicles

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*Weight reduction of vehicle is very important because vehicle weight directly affects energy consumption. Studies researching lightweight vehicle manufacturing process that use polymers are reviewed in this paper. Approaches reducing the weights of vehicles using polymers most frequently involve replacing ferrous and non-ferrous metals with polymers and increasing the specific strengths and rigidities of polymers. Researches into polymers for use in lightweight vehicle are classified into high performance polymers, polymers for weight reduction, reinforced polymer composites, polymer sandwich panels, and polymer/metal hybrid systems. A diverse range of polymer materials can be used to make vehicle components and the manufacturing methods required to produce and work those materials vary greatly. Shaping processes must be chosen according to the materials being used and the product design. Replacement of metal products with polymer materials in current vehicles is limited. Large amounts of lightweight materials, such as polymers, will be greatly used to construct newly developed vehicles, including electric and electric/hybrid vehicles.*

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## 1. Introduction

Vehicle weight reduction is currently the hottest issue concerning vehicles. Vehicle weight directly affects energy consumption and a 10% reduction in weight increases fuel economy by approximately 7%. Fig. 1 shows a trend of fuel efficiency of automobile by year.<sup>1</sup> The recent emergence of electric vehicles has focused attention more on vehicle weight. Vehicle weight reduction can be achieved by various means employed simultaneously.

These means involve reducing the size and number of engine-related parts by maximizing engine efficiency, producing structurally efficient body design, reducing overall vehicle size by maximizing interior room using space efficient designs, as well as employing lightweight materials.<sup>2-4</sup> Lightweight materials can be utilized by developing effectively advanced materials, pioneered molding processes, and construction technologies. The materials used for vehicle fabrication are largely classified as ferrous metals, non-ferrous metals, and polymers. Fig. 2 shows material consumption ratio for a light vehicle.<sup>5</sup>

In this paper, studies researching lightweight vehicle manufacturing

process that use polymers are reviewed. Approaches reducing the weights of vehicles using polymers most frequently involve replacing ferrous and non-ferrous metals with polymers and increasing the specific strengths and rigidities of polymers. Developing novel polymers and improving the material properties of existing polymers are two common approaches to replacing metal with polymers. Most of the interior parts of an automobile are well known polymers. Additionally, several invisible interior and exterior parts of a car have traditionally been made of metals; however, many of them are now being replaced with polymer-based parts. The parts that can be replaced with polymers vary according to class and type of vehicle. Currently, approximately 15 to 20% of the total weight of a vehicle is polymer materials. Typical parts that are being replaced with polymers are front ends, bumpers and fascia systems, grills, fenders, intake manifolds, engine mounts, door structures and panels, door impact beams, bonnet panels, under hood parts, pedal boxes, body structures, steering columns, wheel rims, seat backs and under parts, roof modules, sun roofs, interior trim components, instrument panel, etc.<sup>6-9</sup> Table 1 shows applications of polymers in automobile parts and Table 2 shows amount of polymers used in automobile parts.<sup>10</sup>

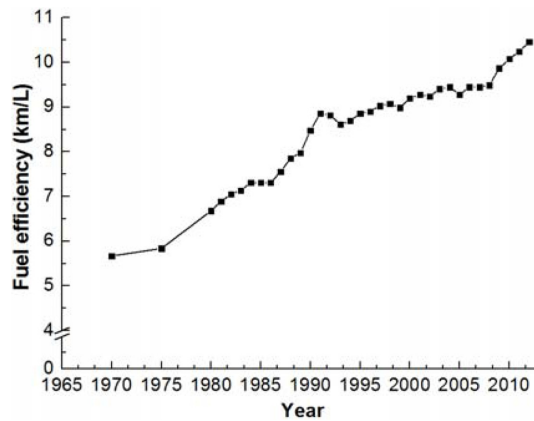


Fig. 1 Fuel efficiency of automobile by year

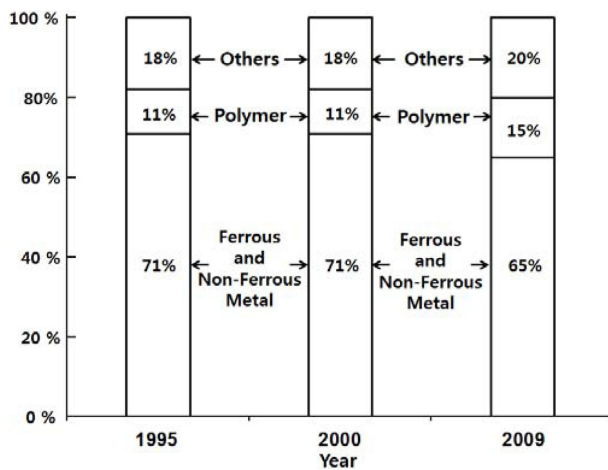


Fig. 2 Material consumption ratio for a light vehicle

## 2. Research Trends in Polymers for Vehicle

### 2.1 High performance polymers

Generally thermoplastics are more popular than thermosets for automobile parts manufacturing because shaping thermoplastics is simpler and faster. Materials to be applied near engine parts should have high thermal resistance, whereas exterior and structural parts should be fabricated from materials with high mechanical strengths. Thermoplastics, however, have limited thermal resistance and mechanical properties, and thus, can be applied only after they are modified for high performance polymers through reinforcements.

After PA (Polyamide, Nylon) emerged in the late 1930s, high rigid and thermally resistant engineering plastics have been in the limelight. Commodity plastics include PE (Polyethylene), PP (Polypropylene), PS (Polystyrene), PVC (polyvinylchloride), PMMA (polymethylmethacrylate), ABS (Acrylonitrile-butadiene-styrene), etc. and engineering plastics that have high mechanical strength and thermal resistances are PC (polycarbonate), PA, POM (polyoxymethylene), Polyester, etc. Development of most of these engineering plastics began in the 1970s. Examples of super engineering plastics, plastics that have better mechanical properties, and much better thermal resistances than engineering plastics, are PPS

Table 1 Applications of polymers in automobile parts

Polymer Name	Properties	Application Examples
Polypropylene	Low-cost, good solidity, chemical resistance	Bumpers, wheel housings, air filter housings, guide chnnels, containers, side panels, bettery case, door trim, crash panel
Polyurethane	Damping, good elasticity, low heat conductivity	Seat upholstery, dashboard and roof padding, exterior elements
Acrylonitrile Butadiene Styrene Copolymer	Electroplatable, dimensionally stable, solid	Interior paneling, wheel panels, radiator grills, dashboard
Polyamide	Temperature-stable, low gas permeability, permanently solid, rigid, ageing-resistant	Motor covering, suction elbows, wheel panels, plugs, mirror housing, door handles, connector housing
Polyvinylchloride	Weather-resistant, low-cost, non-inflammable, good haptics	Underbody protection, protective bordering, cable insulation, interior paneling
Polyethylene	Low-cost, ageing-resistant, chemical resistance, good solidity	Fuel tanks, windshield fluid containers
Polyoxymethylene	Chemical resistance, abrasion-resistant, impact-resistant, low tendency to creeping, thermally stable	Clips, connectors, bearing components
Polymethyl-methacrylate	Transparent, scratch-resistant, UV-resistant, stress-cracking resistant	Headlight lenses for blinker and rear lamps
Polycarbonate	Impact-resistant, transparent, UV-resistant	Headkight lenses, tail light cover, bumper coverings, exterior auto body parts
Polyethylenetere-phthalate	Tensile strength, rigid, good barrier effect	Textiles, coverings, seat belts, airbags
Polybutylenetere-phthalate	Rigid, heat-resistant, good electrical insulating, behavior, dimensional accuracy	Electronic housings, bumper coverings, exterior auto body parts, plugs, connector housing
Polyether-etherketone	Heat-resistant, friction-wear properties, chemical resistant	Oil pump, bearing, washer, transmission parts, ball joint, brake parts

(polyphenylene Sulfide), PES (Polyethersulfone), PAI (Polyalkyleneisophthalate), PAR (Polyarylate), PEEK (Polyetheretherketone), PEI (Polyetherimide), PI (Polyimide), PTFE (Polytetrafluoroethylene), and LCP (Liquid Crystalline Polymer), and most of these were developed after the 1970s. The historical progress of polymers reflects the fact that the synthesis technologies used for the preparations of novel polymers were developed in accordance with the needs for polymers with higher mechanical strengths and thermal resistances. These high performance polymers are used in automobile parts alone, as alloys, and with reinforcements. Compound-type polymers are widely used since developing synthetic methods for producing multi-functional polymers takes a long time and is costly. Compound-type polymers are manufactured by mixing and

Table 2 Amount of polymers used in automobile parts

Part	Main Plastic Type	Weight in Average Car (kg)
Bumpers	PP, ABS, PC	10.0
Seats	PUR, PP, PVC, ABS, PA	13.0
Dashboard	PP, ABS, PA, PC, PE	15.0
Fuel Systems	PE, POM, PA, PP	7.0
Body (Including body panels)	PP, PPE, PBT	6.0
Under the Hood Components	PA, PP, PBT	9.0
Interior Trim	PP, ABS, PET, POM, PVC	20.0
Electrical Components	PP, PE, PBT, PA, PVC	7.0
Exterior Trim	ABS, PA, PBT, ASA, PP	4.0
Lighting	PP, PC, ABS, PMMA, UP	5.0
Upholstery	PVC, PUR, PP, PE	8.0
Other Reservoirs	PP, PE, PA	1.0
Total		105.0

compounding polymers with reinforcements and additives. This approach is much easier and simpler, in most cases, than synthesizing polymeric materials with new functionalities.<sup>11-15</sup>

Polymers have advantages, in addition to their ability to reduce weight, for vehicle part applications. Polymers inherently self-lubricate and can be used in bearings, gears, and ball-and-socket joints. A one-time injection of lubricant would be enough to sustain a polymer ball-and-socket joint in a vehicle until it went to the junkyard. This cannot be expected of metal ball-and-socket joints. Polymers used in bearings and gears include PA and POM, usually reinforced with glass fibers. Polymers can also reduce vehicle noises and vibrations, which can increase driving comfort.<sup>16-18</sup>

## 2.2 Polymers for weight reduction

The walls of polymer products are thicker in many cases in order to increase their strengths. Thicker walls are heavier. Forming foams, bubbles, or cells in a component's construction material can obviously reduce a product's weight. This method originated at MIT in the 1980s, commercialized by Trexel Inc., and was named Mucell process. In this method, microcellular foams are developed during injection molding. In the Mucell process, polymers are melted in the injection unit of the injection molding machine and then a supercritical fluid is dissolved in the melted polymer using a physical blowing agent (PBA), such as N<sub>2</sub> and CO<sub>2</sub>. Then, the melted polymer, containing the supercritical fluid, is injected using by high pressure, into the mold cavity and allowed to solidifying. Cell sizes are approximately 1-100  $\mu\text{m}$  and their densities range between 109 and 1015 cells/cm<sup>3</sup>. Cell size and density depend on supercritical fluid concentration, which is controlled through gas saturation, microcellular processing pressure, and mixing temperature during processing. Various polymers are used in this process, such as PPS, PS, POM, PET (Polyethyleneterephthalate), TPE (Thermoplastic Elastomer), PP, HDPE (High Density Polyethylene), PA, and PC. Weight reductions of approximately 10-60% can be achieved, depending on the materials, using this process. Products containing foams also demonstrate better thermal insulation properties. Some problems can arise during the foaming processing, such as the swirl marks on the molded surface as a result of trapped air, silver streaks on the surface

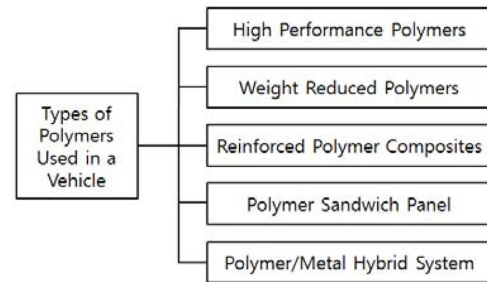


Fig. 3 Types of polymer materials used in a vehicle

as a result of bubbles breaking, surface blistering, and post-blowing. These attributes deteriorate surface quality and limit the applicability of the process. Mechanical strength drops markedly when the size of the foam exceeds 0.25 mm, thus research into overcoming these problems is needed. One approach to overcoming these problems is to use injection compression molding instead of injection molding. Injection compression molding leads to enhanced control of microcellular structure. In many cases glass fibers are added to polymers during this process to enhance the mechanical properties of the final products. Chemical blowing agents are used in glass fiber reinforced PP to reduce its viscosity and prevent fibers breakage. When rubber particles are added, impact and fracture toughening properties increase. Injection ready pellets can be made by extruding them with a twin screw extruder, within which the polymer and blowing agent are mixed. Injection molding is then performed using these pellets. This approach is called supercritical fluid laden pellet injection molding foaming technology (SIFT).<sup>19-24</sup>

The other process used to form microcellular foams follows. The mold cavity is filled with the beads that contain the blowing agent and then high temperature steam is injected into the mold cavity to bond the beads. The temperature and pressure of the steam greatly affect the mechanical properties and property uniformities of the resulting products. This process is called steam chest molding. The mold opening is controlled during this process to adjust the foam size through pressure variation. Gas venting is very important in this process and the mold contains many vent holes. PP, PE, and PS are mostly used for this process. Blowing agent containing resins, such as commercially available EPP, EPE, and EPS are called expandable resins. Of them, EPP shows high impact strength, high-energy absorption, and high heat and noise insulation. Therefore, it is a material with high potential for use in vehicles.<sup>25-28</sup>

## 2.3 Reinforced polymer composites

Attempts have been made to incorporate polymer nanocomposite-based parts into vehicle since the 1960s. A nanoscale clay was dispersed in a polymer matrix and the resulting composite was used to construct automobile parts located near the engine since the nanocomposite had good thermal properties. Many studies into polymer nanocomposites followed this. Clay nanocomposites with PP, PA, PBT (Polybutyleneterephthalate), PC, etc. have been reported. Clays such as montmorillonite can be spread to nanoscale thicknesses to produce what are called layered clay minerals. When nanoscale clays are dispersed in polymers, their thermal resistance and flame retardance

increase. The most significant aspect of clay nanocomposites is how one can disperse the nanoclays in the polymer matrix since the material properties of the nanocomposites strongly depend on their nanoparticle dispersion. Full exfoliation or intercalation of nanoclays in a polymer matrix secures the properties of the nanocomposite. However, strictly speaking, full exfoliation or intercalation of nanoparticles in a polymer matrix can only be achieved in situ. Polymer nanocomposite preparations have limitations since mixing and compounding in a melt using a continuous mixer, such as a twin screw extruder, cannot secure fully exfoliated or intercalated nanoparticles.<sup>29-34</sup>

In contrast to nanocomposites, polymer composites that exhibit a wide range of properties can be achieved through various convenient manufacturing processes. These polymer composites are achieved by compounding reinforcements with polymers or molding polymers with a preset preform simultaneously in the mold. Reinforcements are usually mineral fibers, such as glass fibers, carbon fibers, boron fibers, and basalt fibers. Polymer fibers, aramid fibers and PE fibers are also used. The mechanical strength and stiffness of a polymer composite depend on the content, type, and shape of reinforcement used. Fibers used in fiber reinforced polymer composites are designated as discontinuous fibers or continuous fibers, according to their forms. Discontinuous fibers are short fibers, long fibers, and chopped strand mats. Continuous fibers are continuous fiber mats, unidirectional or multi-axial laminates, woven fabrics, knitted fabrics, and braided fabrics (Fig. 4).<sup>35-43</sup>

Manufacturing processes for producing parts with fiber reinforced polymer composites are diverse. Short glass fibers (typically < 3 mm) reinforced polymer composites are used in conventional injection molding, long glass fibers (typically 3-25 mm in length) reinforced polymer composites are used in extrusion-compression and sheet extrusion processes. Continuous fiber and woven fabric containing polymer composites are used in pultrusion, thermosetting, and compression molding. The compression molding process was adopted for manufacturing parts with thermoset-matrix composites and uses sheet molding compounds (SMCs) as starting materials. A SMC is a thin sheet containing glass fibers, most of which are approximately 25 mm in length, in a thermosetting resin. When para-aramid fibers (such as Kevlar) or carbon fibers are used as reinforcing fibers in SMCs, these composites can replace metal. Racing cars already use these composites. The most common thermoset resin systems are polyester, vinylester, epoxy, phenolic, and bismaleimide.<sup>44-47</sup>

Molding thermoset parts reinforced with glass fibers during reaction injection molding (RIM) is called reinforced reaction injection molding (RRIM). The thermoset resins usually used are polyurethane and polyurea, and short glass fibers are used with RRIM. When using long fiber mats in RIM, the preset preform is first inserted into the mold and then RIM is performed. Finally, the thermoset is cured. Reinforced polymer composite parts also can be made using RTM by presetting the preform in the mold and then feeding the thermosets. Reactants are fed separately and they meet and are mixed in the mixing chamber, then the mixed reactants are injected into the RIM mold. In contrast, in RTM, premixed reactants, held in the reservoir, are fed into the mold by a plunger. RTM involves low flow velocity and low resin viscosity. Thus, the location of the reinforcement is stable in the mold during molding. Preforms used in RTM are manufactured by spraying fibers and binder into perforated molds or heating and pressing mats and/or

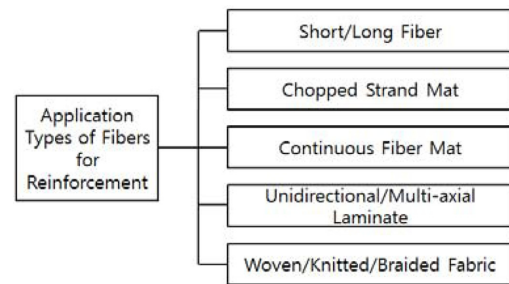


Fig. 4 Application types of fibers used to reinforce polymers

fabrics with thermoplastic binders.<sup>48-53</sup>

## 2.4 Polymer sandwich panels

Polymer sandwich panels and structural composites have two types of core geometries, solid and spatial. The properties of structural composites depend on the properties of their core layers and the geometric arrangements of their core structures.

Polymer sandwich panels with solid core are manufactured by RTM thermosets after presetting glass fiber laminates into the molds. Thermoset resins form skin layers during this process. This process has the advantages of lower processing costs and higher surface qualities, compared to SMC, and it is suitable for smaller numbers of products. Carbon fibers or para-aramid fibers can be used for reinforcement when core layers are manufactured using reinforced thermoset resin (such as epoxy) laminates. Laminated core layered polymer sandwiches are similar to polymer composites and their rigidities are poor compared to structural core layered polymer sandwich panels.<sup>54-57</sup>

Polymer sandwich panels consist of core and skin layers. The mechanical properties of polymer sandwich panels depend on the geometrical structures of their core layers and the mechanical properties of their skin layers. Using foam structures for core layers instead of the solid structures produced by RTM produces components with better mechanical properties and smoother surfaces than SMC does. The mechanical properties of foam cored polymer sandwich panels vary with the size and density of foam used, and those parameters should be well controlled during molding. If the structure of the core is consistent instead of being a random foam, then it is easy to control the mechanical strength to be high and uniform. The most typical core layer structure is the honeycomb. Applications of polymer sandwich panels vary since sandwich panels with new functions can be achieved by imposing special properties onto core layers. Highly rigid honeycomb structures can be made from meta-aramids such as Nomex, and flame retardant PEI can be used for honeycomb materials. This means that varieties of materials and structures of core layers can be used to obtain polymer sandwich panels with highly variable properties.<sup>58-66</sup>

If one designs polymer sandwich panels that contain full three-dimensional core structures instead of two and a half dimensional structures like the honeycomb shape, mechanical properties can be greatly improved. This kind of core design has been attempted on metal sandwich panels and recently it has also been applied to polymer sandwich panels. Many consider the kagome structure to be the best core structure design. Polymer sandwich panels with kagome-structured pyramidal cores show high rigidity, high energy absorption, and high

impact resistance. Thus this design is very attractive for vehicle materials. Complete adhesion between skin and core layers is very important for these structural sandwich panels and the strong points of these panels are only secure once perfect adhesion has been achieved.<sup>67-73</sup>

## 2.5 Polymer/metal hybrid systems

Combining two different materials in vehicle parts began in the 1920s when steel chassis were combined with timber-framed aluminum bodies. After the appearance of this hybrid system, it evolved into steel chassis with glass fiber reinforced polymer bodies. Polymer/metal hybrid systems are classified into two types: sheet metal/reinforced plastics (two layers or two components) and sheet metal/plastic foam/sheet metal (three layers).<sup>74-76</sup>

Joining plastics to metals is usually accomplished during molding. The most common approach is to use an insert injection molding method. The preset metal insert is placed in the mold cavity and then thermoplastics are injected into the cavity after closing the mold. The metal is buried and fixed in the thermoplastic. Crystalline thermoplastics, such as PA and PBT, have advantages for insert molding since they allow for residual stress relaxation. Glass fiber containing crystalline thermoplastics are suitable for metal insert molding because the differences between the thermal contractions of the metals and those of the plastics are small.<sup>77-79</sup>

Thermosets/metal hybrid parts can be prepared by RIM. The RIM process can be described as follows. Two or more components are fed into the mixing chamber and then the mixed components are injected into the mold. The mixed components polymerize (cure). The metal is inserted into the mold, RIM is performed with PU, and then a metal/PU hybrid composite is obtained. Introducing glass fibers during RIM reduces the difference between the thermal expansion coefficients of the two materials. Like RIM, RTM also can be used to manufacture thermoset/metal hybrid parts. Thermosets that can be used in insert RTM are epoxy, vinylester resin-based systems, and PU. Controlling insert RIM and insert RTM processes is somewhat complicated and they make recycling composites difficult.<sup>80-82</sup>

## 3. Closing Remarks

A diverse range of polymer materials can be used to make vehicle components and the manufacturing methods in accordance with products and materials vary greatly. Shaping processes must be chosen according to the materials being used and the product design. Thus, our ability to replace metal products with polymer materials in current vehicles or vehicles designed to be made of metal is limited. Consequently, large amounts of lightweight materials, such as polymers, will be greatly used to construct newly developed, polymer-based, vehicles, including electric and electric/hybrid vehicles. This reduces vehicle weight remarkably.

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