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Technical developments and market trends of automotive airbags

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Abstract: Airbags are used in modern cars as a passive safety system for drivers and passengers. The bags are made of closely woven fabric largely coated with an elastomer. Nylon 6.6 is the predominant fibre in making airbag fabric. An airbag is connected to an inflator that is activated by the impact from an accident. Airbags are folded with care and efficiency and stored in the steering wheel, glove compartment and in other appropriate places in a car to ensure smooth deployment in the event of an accident. The actual performance of an airbag is closely related to its deployment behaviour. Currently airbag markets are largely controlled by three global regions – Western Europe, Northern America and Japan. Approximately 220 million airbags are expected to be fitted in cars globally in 2008. It is expected that the future growth of the airbag markets would come from China, India and Korea. Pedestrian safety is becoming a big issue in Western Europe and Japan. It might open up new opportunities for automotive airbags in these geographical regions.

Key words: automotive, airbags, airbag yarns, airbag sewing threads, air permeability, coated fabric, cover factor, crash speed, deployment, hot gas, inflator, industrial textiles, nylon 6, nylon 6.6, nylon 4.6, polyester, safety system, side curtains, woven fabric.

12.1 Historical background

John Hetrick was the father of the automotive airbag. He was granted a patent in the USA in 1953 for developing an automotive safety cushion assembly. Hetrick's idea was executed in automobiles through commercial production of vehicles with airbags by General Motors in the USA in the early 1970s. Nonetheless, the concept did not successfully take off due to lack of public interest in an expensive complicated and less effective technology. But the concept of automotive safety cushion assembly was never discarded. Further research enabled scientists to come up with a much improved, effective and more economical airbag system. In 1984, the concept of airbags as a passive safety system was used as a standard item in Mercedes Benz S-class cars. From the late 1980s most European, American and Japanese automobile manufacturers widely started using airbags for drivers and front seat passengers in modern cars to reduce mortality and serious injuries in the event of head-on collision.

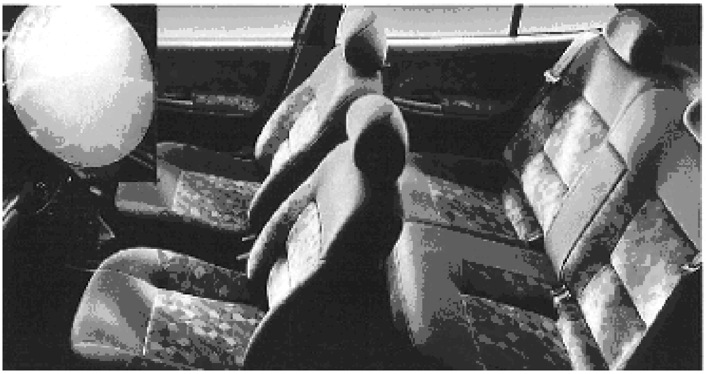
Figure 12.1 shows the inside view of a modern car made in 1997 with driver airbag deployed. From 1998 it became a legal requirement in the USA for all new vehicles to have driver's and passenger's airbags. Fitted side curtains have become more of a common safety feature in European and American cars for saving lives in the event of a rollover collision. Side curtains will become a legal requirement for cars and light trucks to be made in the USA from 2009. Today sales of new cars are bolstered by the inclusion of several airbags in a car and they appear to add extra value in the eyes of consumers for safety and security in the event of an accident. From early 2000s, Toyota Avensis started providing 9 airbags, Audi A8 10 airbags and BMW 7 series 12 airbags as standard.

Airbags are closely woven textile envelopes that are mostly made up from nylon 6.6 filament yarns. An attempt was made unsuccessfully in the past to use nylon 6 yarns to make airbag fabrics. Currently polyester (PET) and nylon 4.6 filament yarns are used in small quantity for airbag fabrics and airbag sewing threads in some parts of the world. Nylon 4.6 behaves very similarly to nylon 6.6 but it is much more expensive. Polyester (PET), however, is a cheaper substitute but technically inferior. Table 12.1 highlights the relative merits of nylon 6, nylon 6.6 an polyester yarns for airbag application.

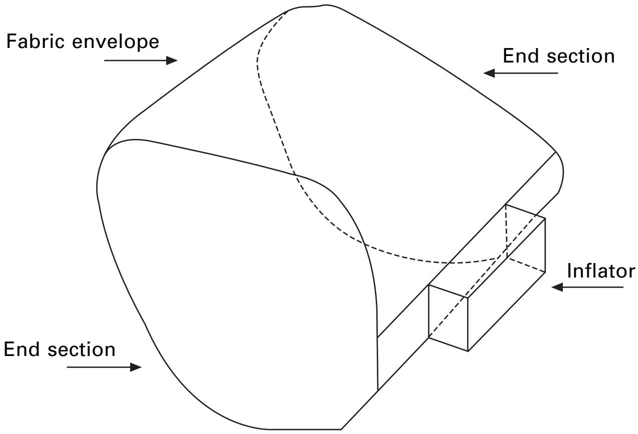
Table 12.1 Characteristics of various polymers for airbag yarns

Polymer characteristics	Nylon 6.6	Nylon 6	Polyester (PET)
Density (kg/m^3)	1140	1140	1390
Specific heat capacity (kJ/kg °K)	1.67	1.67	1.3
Melting point (°C)	260	215	258
Softening point (°C)	220	170	220
Heat to melt (kJ/kg)	589	522	427

Sources: various



12.1 The interior design of a modern car with deployed airbag.



Source: US Patent 5375878, 1994

12.2 The schematic design of a passenger airbag attached with an inflator module. Source: US Patent 5375878, 1994.

An airbag is designed to open up from an impact (for most cars in the case of an impact in the front but for more advanced and expensive cars, appropriate airbags can be deployed on an impact on sides or at the back) in the car arising from a collision. Following a collision and bag deployment, an inflated airbag acts as a cushion or an energy absorber and prevents the occupants from striking any solid fixed parts of the car. An automotive airbag is connected to an inflator that is activated by the impact from an accident. Within a few milliseconds following an impact, the inflator fills the bag with nitrogen-rich gas or with another appropriate inert gas. On activation, the inflators produce mainly hot gas by activating a propellant to fill the bags. The textile envelopes (see Fig. 12.2) or airbags are made and very often appropriately coated to contain hot air produced by a small explosion arising from the activation of sodium azides or similar compounds (called propellants) while being impacted.

12.2 Materials and processes

The fabric used in making airbags needs to be strong, tough, hard wearing with low and controlled air/gas permeability behaviour. Nylon 6.6, as discussed in the previous section, is the material of choice for the yarn. Nylon 6.6 yarns made for airbags are strong, tough, resilient with good thermomechanical responses up to 200°C.

In the 1980s first generation airbags were largely made of 940 dtex and 700 dtex nylon 6.6 yarns with neoprene coating. The first generation materials were aimed at making drivers' and passengers' airbags meet requirements such as defined package volume for the storage compartment, good foldability, high softness, resilient, heat resistant and low air permeability. However, as more and more airbags were being fitted into cars, automotive manufacturers raised their requirements for technical performance of airbags. Amongst new performance criteria, high dynamic stress resistance to successfully withstand high crash speed, low fabric weight for lesser impact on the human body on bag deployment, higher fabric strength and greater air tightness for rollover protection. Hence in the mid-1990s airbag manufacturers brought second generation materials into the market. As a result 940 dtex yarn as an airbag material became virtually obsolete and 470 dtex and 700 dtex high tenacity nylon 6.6 yarns became the materials of choice. Also neoprene coating was mostly replaced with silicone coating for the bags. Also for curtain airbags used in rollover accidents, one-piece densely woven bag in combination with silicone coating for sealing was introduced to comply with air tightness requirements for rollover protection. As the market moved on and more and more automobiles in Western Europe, North America and Japan were fitted with airbags, a need was felt for third generation materials at the turn of the century. The requirements from the automotive manufacturers were raised to even stronger and lighter bags with lower and more controlled air/gas permeability. It was also expected that the new materials should be gentle on the skin during impact, with better packability and greater resistance to heat conductivity. In making third generation airbags, super high tenacity 470 dtex nylon 6.6 yarns were used with lighter fabric structure and more defined silicone coating. In the last 3 to 4 years, the market has been seriously evaluating 235 dtex nylon 6.6 high tenacity yarns as the next generation airbag material. Table 12.2 highlights the physical properties required in making good quality airbag fabrics.

In manufacturing airbag fabrics, the warp yarn is supplied on a beam. The yarns in the warp beam are normally sized to withstand loom-state friction and also to prevent yarns from rolling during drying and wind up. Various additives are used in the size recipe to reduce fabric fraying, yarn pull-out and distortion. Normally airbag fabrics are tightly woven with 1/1 structure and largely the fabrics are woven involving rapier and air-jet looms. However, airbag fabrics are now being woven on water-jet looms too. Today loom

Table 12.2 Airbag yarn characteristics

Yarn characteristics	Medium to high tenacity yarn	High to super high tenacity yarn
Tenacity (cN/tex)	72–78	80–85
Extensibility (%)	20–22	18–20
Hot air shrinkage @ 180°C (%)	8–9	6–7
Filament fineness (denier)	2.8–3.0	6.0–6.5

Sources: various

speeds in excess of 550 ppm (picks/minute) on rapier machines, 650 ppm on air-jet machines and 900 ppm on water-jet machines are achievable in airbag fabric construction. Water-jet looms are highly efficient and cost effective. Jacquard weaving machines are normally used to weave one-piece curtain bags. The fabric make-up and the actual size of driver and passenger airbags are quite different. American automotive airbags are somewhat larger than similar airbags for European or Japanese cars. Also irrespective of geographical location, passenger airbags are larger in size and consume more fabric than driver airbags. For example, depending on the size of a car and the country of origin, a driver's airbag consumes between 0.6 and 1.5 square metres of fabric, whereas a passenger airbag consumes between 3 and 4 square metres of fabric. Side curtain, a one-piece woven bag, normally consumes between 3.5 and 4.5 square metres of fabric.

After weaving, the airbag fabrics are normally scoured to remove size from the material. The complete scouring operation uses three to four wash boxes that are separated by a vacuum extraction system to capture the extracted size. Following scouring, fabrics are calendared and heat-set to achieve dimensional stability and a precise control of air permeability in downstream application. Finished fabric air permeability can be well engineered if a balance between temperature, tension, dwell time and pressure between the calendar rolls is appropriately maintained.

Currently the automotive industry uses both uncoated and coated fabrics in making airbags. For coated bags, silicone is the most common coating material. Perhaps it is worthwhile to mention here that the airbag industry has been debating for at least the last 10 years the relative merits of coated and uncoated fabrics for airbags. The coated airbag is considered to be environmentally unfriendly but it offers greater resistance to heat conductivity and tearing performance along with low air/gas permeability. However, the uncoated airbag is more environmentally friendly. It is easier to fold and pack into small spaces.

For coated fabric, materials need to go through a defined coating operation. Today's choice of an elastomer for coating is mainly silicone. In processing, silicone is applied as a single coat by blade technique. Depending on the type of fabric and finished fabric requirements, an amount of 50 to 80 g of silicone is consumed to coat a square metre of fabric. Once the elastomer is spread on the fabric it passes through an oven under tension to induce polymerisation and adhesion between the fabric substrate and the elastomer. The precise time and temperature settings of the oven depend upon the silicone formulation. When coating of an elastomer as a continuous layer is applied on a fabric, the pores of the fabric are blocked. Hence in the event of a coated fabric airbag deployment, airbags are expected to deflate through vents. High technology silicone coating is widely used to make lightweight airbag fabrics that are flexible, durable and less prone to degradation over

Table 12.3 Mechanical performance of coated airbag fabrics

Performance parameters	Values
Yarn	470 dtx
Weave	Plain 1/1
Construction (threads/cm)	Various
Thickness (mm)	0.32–0.37
Weight (g/m^2)	220–240
Strength (kg/5 cm)	280–320
Elongation (%)	33–36
Tear strength (kg)	10–12

Sources: various

time. Table 12.3 illustrates mechanical performance of silicone-coated fabrics extensively used by the automotive industry for airbag application.

In the early to mid-1990s, airbag fabrics were largely coated with neoprene or silicone elastomers. These coated fabrics were found extremely stable in containing hot gas during deployment. However, the shortcomings of coated fabrics were established and they were proven to be their excessive thickness (particularly for neoprene coating), inability to be folded into small spaces and the tendency to degrade rapidly over time. Also concerns were expressed on possible unpredictable degradation behaviour over a period of time that could lead to catastrophic failure if the bag was deployed several years after it was fitted.

For uncoated airbags, the fabric needs to be particularly dense and of extremely high quality. Definitely in manufacturing that kind of fabric, significant pressure can be created on pricing of the materials. However, performance of high quality uncoated fabric for airbags can be more predictable over a period of time. The uncoated airbag releases the gas mainly through the fabric pores and hence it can be deployed at a relatively lower pressure with a cooler gas. Thus it minimises chances of burn injuries and face/neck injuries during deployment.

Considering technical performance relating to safety and environmental needs, the automotive industry prefers driver airbags to be made of lighter silicone coated fabric and the passenger airbags are made of relatively heavier uncoated fabric. The weight of coated fabrics for driver airbags ranges from 180 to 240 g per square metre and for the uncoated fabrics for passenger airbags, the weight ranges from 240 to 260 g per square metre. All in all a passenger airbag is somewhat stiffer and thicker (fabric thickness 0.3–0.4 mm) and a driver airbag is relatively more pliable and finer (fabric thickness 0.24–0.27 mm). Perhaps it is worthwhile to mention here that over the years airbag inflator technology has changed radically with the gradual introduction of augmented compressed gas and solid pyrotechniques other than sodium azide. The new inflators generate hotter gas than sodium azide which in turn has created a greater consumption of silicone coated fabrics in Europe.

The finished airbag fabric is cut into panels and sewn. The best method of cutting either coated or uncoated fabric is to use lasers. The technique is efficient and accurate. It fuses the edges of the fabric to prevent fraying. The normal design of the driver size bag is two circular pieces of fabric sewn together whilst the passenger bag is tear-drop shaped, made from two vertical sections and a horizontal panel. Airbags are normally sewn with sewing threads made of either nylon 6.6 or nylon 4.6 yarns. The sewing pattern and stitch densities are chosen carefully to maximise the performance of the bag. High density stitching has been developed to provide less leakage through seams. Also special 'seal and sew' assembly technology has been developed particularly for side curtains to meet air pressure retention requirements. In this process an adhesive is applied to the area to be stitched before the stitch is made. Adhesive in this case acts as a gasket on a coated or immersed fabric.

Like a parachute, airbags are folded with care and efficiency to ensure smooth deployment. A variety of folds are found suitable (examples: accordion fold, reversed accordion fold, pleated accordion fold, overlapped folds, etc.). Once the bag is folded, it is coupled with the necessary electronics and the deployment system within the casing for successful activation in the event of an accident. In the airbag supply chain pipeline, yarn manufacturers, weavers, bag manufacturers and system manufacturers are the major players. Table 12.4 outlines some of the major global players in the airbag supply chain.

12.3 Airbag deployment and performance criteria

Normally a car fitted with airbags is mounted with a pair of sensors in the front bumper. In the event of an accident, the sensors evaluate the severity of the impact and make an intelligent decision whether to deploy the airbag

Table 12.4 Airbag supply chain

Yarn manufacturers	Weavers	Airbag manufacturers (cut and sew airbag)	System manufacturers (assembled airbag kit)
INVISTA	BST	ASCI	TRW
PHP	UTT	TRW	AUTOLIV
SOLUTIA	MILLIKEN	AIL	PETRI (TAKATA)
TORAY	NCV (PORCHER)	AERAZUR	BREED
TOYOBO	FOV	SVENSKY	
RHODIA	AIL	WOODVILLE	
Others		BREED	
		TAKATA	

module. Mostly the cars with airbags are designed such that if they hit an object at a speed normally exceeding 22 km/h, the system will be activated and the bags will be deployed. In actual operation, an impulse is sent, within 5 ms following an accident, to the ignitor which in turn lights a propellant and releases a stream of hot gas rich in nitrogen. The gas surges through the inflator into the bag. The bag deploys with high force through its mountings. Bags are stored behind the mountings in the steering wheel (for driver), in the glove compartment (for front seat passenger) and in the back of the front seats (for passengers in the back seats) and on the window ledges for curtains (for rollover protection). The deployment occurs within 40 ms of an accident. After inflation, the bag deflates in a controlled manner through vents and the fabric pores (for uncoated fabric only) until the inertia of the occupant's body comes to a rest. The whole cycle of airbag inflation and deflation is remarkably short and takes a little more than 100 ms. Table 12.5 shows the time sequence of an airbag's various actions following an accident.

The total situation of a bag deployment is particularly violent. The gas pressure inside a driver's airbag reaches 70kPa, and the temperature reaches (for hot gas deployment) close to 600°C (for a few milliseconds). In the airbag module, very often a fabric of high thermomechanical performance is embedded. This fabric acts as a thermal barrier and a filter. When the inflator is activated, hot gas is issued from sodium azide or similar compounds following an exothermic reaction. The high performance fabric in the inflator module not only acts as a cooler for the hot gas but it also separates any ash or debris from the gas before it enters the bag. The Institute of Occupational Health at the University of Birmingham in the UK had conducted some studies on the exposure to the toxic gas and particle phase pollutants evolved during deployment of airbags in a vehicle. It was established that during airbag deployment, a range of pollutants (total inhalable dust, respirable dust, alkaline content, anions and inorganic gases) would be emitted which could cause subsequent illness and respiratory problems. Possible modifications to currently used airbag deployment systems were considered to eliminate a significant part of this problem.

Table 12.5 Approximate deployment timings for frontal airbags and side curtain

Functions	Driver/passenger airbags	Side curtain
Total time from sensing to full inflation	25–30 ms	15–18 ms
Timing for cushion to unfold, positioning with deployment	10–12 ms	10 ms
Average speed of cushion deployment	150–160 km/h	180 km/h
Total performance time	120 ms	5 s

Sources: various

Table 12.6 Airbag key technical parameters and contributing factors

Key technical parameters	Primary contributions
Tensile performance	Yarn strength and fabric structure
Tear performance	Filament count, yarn strength, fabric structure (openness/closeness) and coating
Air permeability	Yarn structure, fabric cover factor and coating
Seam performance	Sewing thread structure and tensile strength, sewing thread loop strength, fabric structure
Inertial loading	Yarn polymer density
Energy absorption	Yarn polymer density
Thermal absorption	Yarn polymer specific heat capacity
Ageing behaviour	Yarn polymer and coating polymer's sensitivity to thermo-oxidative degradation

Sources: various

For an airbag the key technical parameters and the related contributing factors are outlined in Table 12.6.

The performance of an airbag has always been related to the airbag's deployment behaviour. It is believed that relatively slower release of gas would generate a deployed bag that would feel unduly firm. The danger of this kind of performance could be that the airbag being too firm on deployment might cause occupant's upper-body to rebound from the bag causing whiplash injuries in the process. Scientists have enhanced the performance of an airbag by fine-tuning the appropriate interactions between seatbelt functioning and airbag deployment.

It is perhaps important to mention here that the effectiveness of an airbag in the event of an accident will be virtually non-existent if the driver/passengers seatbelts are not functioning at the time of an accident. Recently a mathematical-based high-speed punch technology was developed by SAE International to provide virtual testing of airbag cover design. The technology is expected to assist in material selection and predict system performance at the time of airbag deployment.

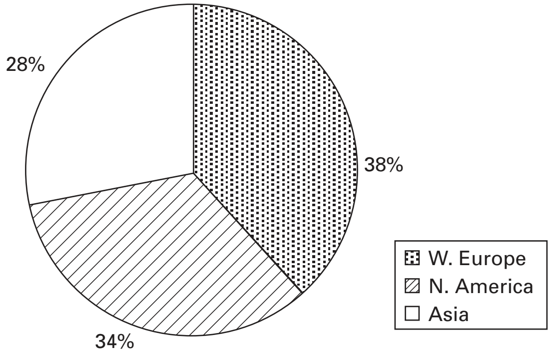
In the event of an accident, the performance of an airbag in saving an occupant's life and injuries will depend on several critical factors and these are as follows:

- on-time sensing, efficient activation of the system and effective releases of gas
- correct deployment and positioning of the bag
- structure and cover factor of the fabric used for the bag
- air/gas permeability characteristics of the fabric/bag, particularly the rate of release of gas through the fabric/bag
- balanced interactions between seatbelt functioning and deployment of the bag.

12.4 Market trends and developments

The airbag industry is one of the youngest members of the technical textile sector but since early 2000 it has been growing between 7 and 10% within the three main global regions: Western Europe, North America and Japan. Currently these three regions control approximately 80% of global airbag markets. Growth in the airbag market in Japan has declined in the last few years as fewer cars are being built there compared to the 1990s. Figure 12.3 shows an approximate breakdown of airbag market shares for Western Europe, North America and Asia for 2004. Growth for driver and passenger airbags for European and American markets were not radically significant in the last few years but side curtains in those markets have grown significantly and expect to grow steadily over the next few years. It is anticipated that a slow down in the overall airbag markets, particularly in Western Europe and North America may happen during 2008 and 2009 because of possible sluggish economic growth. Nonetheless, it is estimated that approximately 220 million airbags will be fitted in cars worldwide in 2008. Table 12.7 shows an approximate growth in the consumption of airbag yarns since 2000 in two main global car-producing regions.

Since mid 1990s the automotive airbag industry has been extremely successful, possibly due to government legislation in the USA and consumer pressure in Europe. There is a guaranteed market for airbags in the USA due to legislation that ensures that every passenger car and light truck (made after 1998) must be fitted with driver and passenger side airbag units. European automotive manufacturers have been in discussions with various governments about enforcing similar legislation in major European countries. However, markets for airbags in Western Europe and Japan have grown steadily in the last 10 years through greater awareness of safety amongst customers. It is also important to mention here that a significant upsurge in growth of the

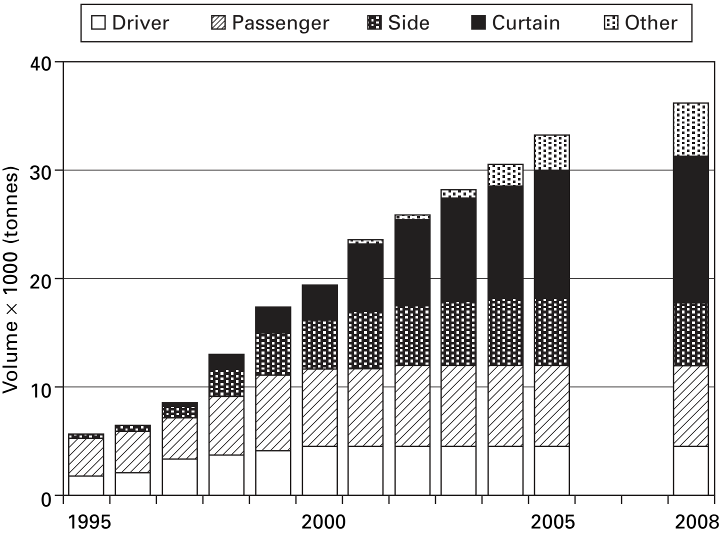


12.3 Regional share of airbag yarn demand for 2004. Courtesy: Alasdair Carmichael, PCI Fibres, UK.

Table 12.7 Approximate consumption of airbag yarns in Western Europe and North America between 2000 and 2008

Year	Consumption (kilotonnes)	
	Western Europe	North America
2000	19.75	21.65
2004	30.97	26.15
2008 (estimated)	36.85	32.30

Sources: various



12.4 West European airbag yarn market by bag type.
Courtesy: Alasdair Carmichael, PCI Fibres, UK.

airbag market since its commercial inception also came from a different angle.

Over time, the use of an airbag as a safety device spread beyond driver and passenger airbags. Now automobiles are fitted with one-piece woven side curtains and even knee bags, thorax bags (to protect chest and ribs), impact curtains, etc. Needless to say, the increased number of airbag varieties and their respective applications require a wide variety of performance functions. Figure 12.4 shows how airbag markets have grown over the years with its variety in applications. With the introduction of different types of airbag systems, different types of crash sensors have become essential. For driver and passenger frontal airbags, a central electronic module equipped with a single accelerometer is used. However, with the introduction of side curtain and head protection systems, additional side sensors coupled with an accelerometer and a microcontroller are necessary.

As discussed earlier, in Western Europe and Northern America, airbag market growth will come mainly from side curtain and thorax bags. However, large growth in the airbag business will come from China and possibly India and Korea in the coming years from driver and passenger airbags. In the next 10 years China and possibly India would be the manufacturing base for growth in the airbag industry. Both China and India have grown significantly in recent years in manufacturing automobiles. Evidence has shown that the airbag manufacturing base has followed its customers as they have relocated and expanded. Also the airbag system suppliers have outsourced either through partnerships and acquisitions or through new start-up and commission processing to take advantage of regions with lower labour and operating costs. It is not unreasonable to postulate that if production in China and India expanded beyond the volume needed to satisfy the local markets, the surplus would be exported to Europe, America and the rest of the world.

In recent years, the streets of Europe have become more congested. It has raised a major consumer demand for safer vehicles that can provide speed control and pedestrian protection. Pedestrian safety is a big issue for Japan and Europe. It has opened up new opportunities for automotive airbags in those two geographical areas. However, pedestrian safety is not an issue in the USA as the number of fatalities per year is relatively small.

In today's cars, airbag systems are activated involving crash sensors when the impact occurs. However, a new generation of pre-crash sensors have been developed with the aim to make vehicles much safer and reduce the severity of the crash. The working principle of this kind of sensor is based on the speed of light. Infrared coded laser light is sent out and reflected from objects in the proximity of the sensor. The decoder calculates the runtime between the emitted and received laser pulse, which correlates with distance of the object. The sensor, which covers the complete vehicle front, is mounted in the wiper area behind the wind screen, close to the rear view mirror.

Based on a large number of market surveys and scientific reports, it has been concluded that fatality rates are fewer in vehicles equipped with airbags than their unequipped counterparts. The concept of airbags or similar structures is currently being considered in lowering human casualties in building collapses. Simulations of collision-impact on fragile objects reveal that impact injuries can be reduced for people indoors from falling debris in earthquake and building collapses resulting from tornados, hurricanes or similar disasters.

Also experiments with motorcycle airbags to reduce injuries in frontal collisions have been conducted for many years. The Japanese company Honda has probably conducted more research, including numerous staged collisions, than any other company. The first commercial production of motorcycles incorporated with an airbag system started with Honda in 2006 with the

12.5 Airbag as a passive safety device for motorcycle. Courtesy: Honda marketing literature, 2006.

Honda Gold Wing model. Figure 12.5 shows Honda's airbag system fitted on a 2006 Gold Wing motorcycle. It is important to remember that Honda's airbag system wasn't designed to prevent the rider being ejected from the motorcycle in the event of a collision. However, a rapid deployment of an airbag after the impact can help to absorb some of the forward energy of the rider and that in essence can help to reduce the severity of an injury following an accident.

12.5 Future expectations and possible challenges

In terms of airbag yarn demand and global capacity of yarn production, currently, there is a reasonable balance between supply and demand. However, it appears that there will be an imbalance in that equation from the year 2009 onwards. Based on the current forecasts, there will be a shortage of airbag yarns of 10 000 tonnes, although new investments by Invista and PHP/Shenma in China will take care of part of that deficiency.

For the future trends in airbag developments, the industry will continue to put more emphasis in the following areas:

- More demands will be on ultra high tenacity yarns with a switch over to lower yarn linear density.

- Greater emphasis will go to higher tear strength and more controlled gas permeability of the bag fabric.
- Next generation bags are expected to have extra toughness (resilience) and better packability.
- Owing to greater use of more and more hot gas deployment, future bag fabrics are expected to have better heat strength retention and thermo-mechanical responses.
- More and more bag fabrics are expected to conform with longer heat/moisture ageing life.
- Seam performance will become more stringent for greater safety.
- Greater emphasis from the automotive manufacturers will be on zero fault quality.
- Intense pressure from the automotive manufacturers will be on lowering the prices for the bag and the deployment system without compromising quality.

Although, for the future, airbag manufacturers will continue to strive to make the bags lighter, more robust, compact and cheaper, in going forward the global automotive industry will be challenged by the consumers in the following areas:

- Unfaltering reliability of the total safety system.
- Highly competitive costs with unique safety features.
- World class service.
- Innovation for greater safety.

Finally, airbags can be a unique safety feature in an automobile but unfortunately the total system is not entirely fool-proof. The environmental fate of sodium azide which is an active ingredient for the deployment system, is unknown. Work done in the department of atmospheric science at the University of Arizona had established that since the mid 1990s demand for sodium azide has exceeded 5 million kg per year and most passenger vehicles sold in the USA contain approximately 300 g of sodium azide. This has greatly increased the potential for accidental environmental releases and for human exposure to this highly toxic, broad-spectrum biocide. Nonetheless, the problem of safely disposing of large quantities of azide will remain as the vehicle fleet ages and is left with the scrap yards.

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13

Key technology developments in textiles for use in automotive tires

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Abstract: Textile reinforcements have been used in the manufacture of automotive tires since their inception. Starting with cotton, the textile types, components and technical attributes have evolved over the years. Today's automotive tire use of textiles is key in obtaining performance parameters such as longevity and comfort. The textiles most widely used in automotive tires are polyester, polyamide and rayon, but they are highly tailored to our industry's needs and are more technologically advanced than normal textile grades. This chapter will discuss the evolution of textile fibers for automotive tire use and expound on the more unconventional textiles being utilized to enhance tire performance.

Key words: tires, industrial fibers, elastometric reinforcement.

13.1 Introduction

In today's fast paced, mobile society, just about every mode of transportation involves the use of a wheel. A simple machine, the automotive wheel (or more commonly referred to as a tire) is typically a pneumatic (air supported) composite structure whose main function is to help carry a load (e.g., people, material) from point "A" to point "B" reliably and with a high degree of comfort. To accomplish this task, the tire needs to transmit driving, braking and steering forces from the vehicle through the tire to the road surface. In addition, the tire is expected to help absorb road surface irregularities, providing a smooth, comfortable, and quiet ride for the occupants. The automotive tire is one of the most complex, highly engineered, composite structures, widely utilized and generally underappreciated by the end user.

In this chapter, we will explore, in further detail, the properties and performance requirements of automotive tires, how the various reinforcement materials and components contribute to tire performance, and review some recent tire developments using new, novel, advanced fiber/reinforcement technology. As we will see, there is more than one way to achieve a desired tire characteristic by utilizing various materials and design options. The closing section will take a look at trends in the automotive world and how this may impact future tire development and hence fiber reinforcement opportunities.

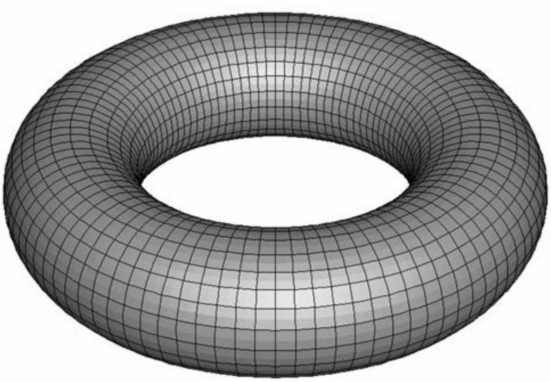
13.2 Properties and performance requirements of tires

13.2.1 Tire performance requirements

A tire is one of the most complex soft composite structures in wide commercial use today. More than 5000 years ago, the Sumerians invented the wheel. John Boyd Dunlop is the recognized inventor of the first pneumatic tire (i.e., bicycle tire) in 1888.[1] In 1895, Andre Michelin was the first person to use a pneumatic tire on an automobile. It was not until 1911 that Philip Strauss[2] invented the first commercially successful automotive tire: a combination tire and an air-filled inner tube.

Technically speaking, the automotive tire geometrically can be considered a torus[3] (Fig. 13.1); that is: a surface of revolution generated by revolving a circle in three-dimensional space about an axis coplanar with the circle, which does not touch the circle. Mechanically, the automotive tire is a flexible membrane pressure vessel. Structurally, an automotive tire is a high performance, soft composite. From a material science point of view, a tire is a compliant, viscoelastic cord/rubber reinforced structure which is subjected to continuous deformations during its life. It is in each of these views that the desired properties and resultant performance criteria are based.

Overall, the tire must meet a vast array of performance criteria to be acceptable by the end users. The automotive tires must support the weight of the entire vehicle, provide efficient mobility, dampen out road textures and irregularities, generate cornering forces for steering control and transmit all traction and braking forces. All this needs to be accomplished through direct contact with the road surface in an area roughly the size of a human hand (Fig. 13.2). In addition, the tire must meet these criteria over a wide range of



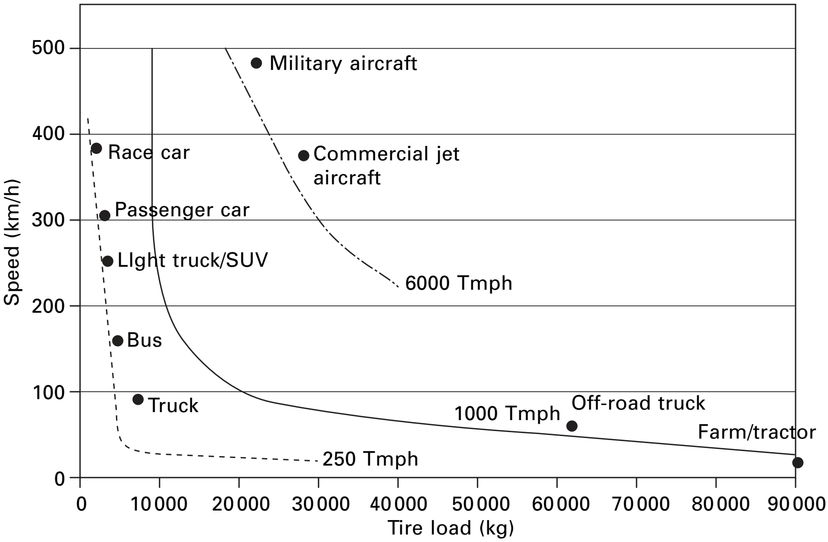
13.1 Automotive tire geometric representation as a torus. (Source: http://commons.wikimedia.org/wiki/image:Torus.png).

13.2 Quintessential automotive tire foot print.

thermal (–20°C to 50°C) and environmental conditions (e.g., dry, wet, snow, ice).

Figure 13.3 depicts a variety of vehicle applications and their respective design load and speed ranges. Comparatively speaking, the automotive tire is designed to accommodate relatively low loads moving at very high rates of speed, in contrast to earth-moving vehicles which carry very high loads at relatively low rates of speed. These basic requirements are then merged with external customer needs such as weather traction, comfort, responsive handling and durability to develop what can be referred to as tire attributes (Fig. 13.4). These tire attributes can be categorized into three general groups: (1) vehicle mobility, (2) performance and (3) comfort/aesthetics. Each set of properties and/or performance requirements are tailored to help achieve the objectives of the vehicle and/or end-customer. The level of importance for each objective will vary depending on the market served and global drivers. For example, European legislation[4,5] is being considered to significantly reduce the "air-borne" noise generated by tires by 2012; hence, new designs/materials that can help reduce tire noise would be a high priority in the European market. Increased handling and response are key drivers for the North American market. In Japan, aesthetics, performance and stopping distance[6] are top drivers.

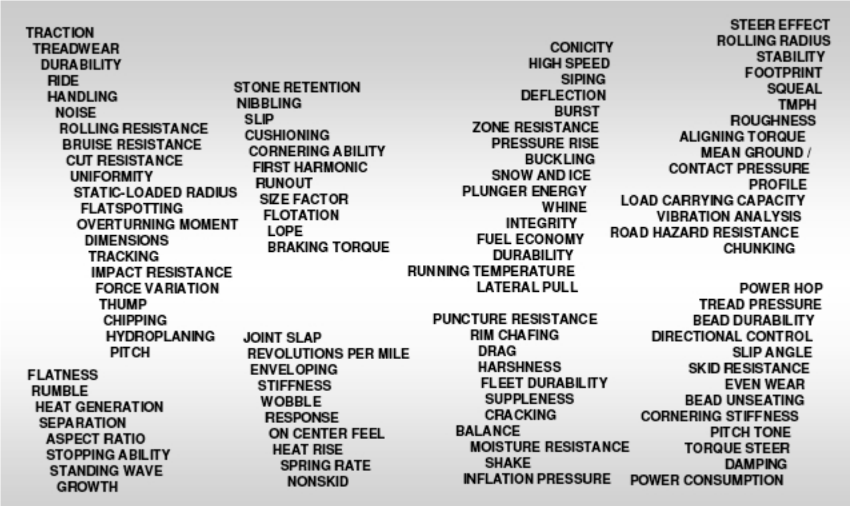
In addition to the broad market needs, there are several niche applications where specific automotive tire designs are needed; for example: run flat, on/



13.3 Tire load carrying capacities and speeds.

13.4 General automotive tire attributes.

off-road applications, and all-season. The combination of needs and drivers governs how tire companies focus their resources to devise, design, and develop new, improved automotive tires with measurable performance enhancements for our customers. All told, there are arrays of product performance characteristics that an automotive tire could be asked to satisfy prior to being released into the marketplace (Fig. 13.5). The exact performance



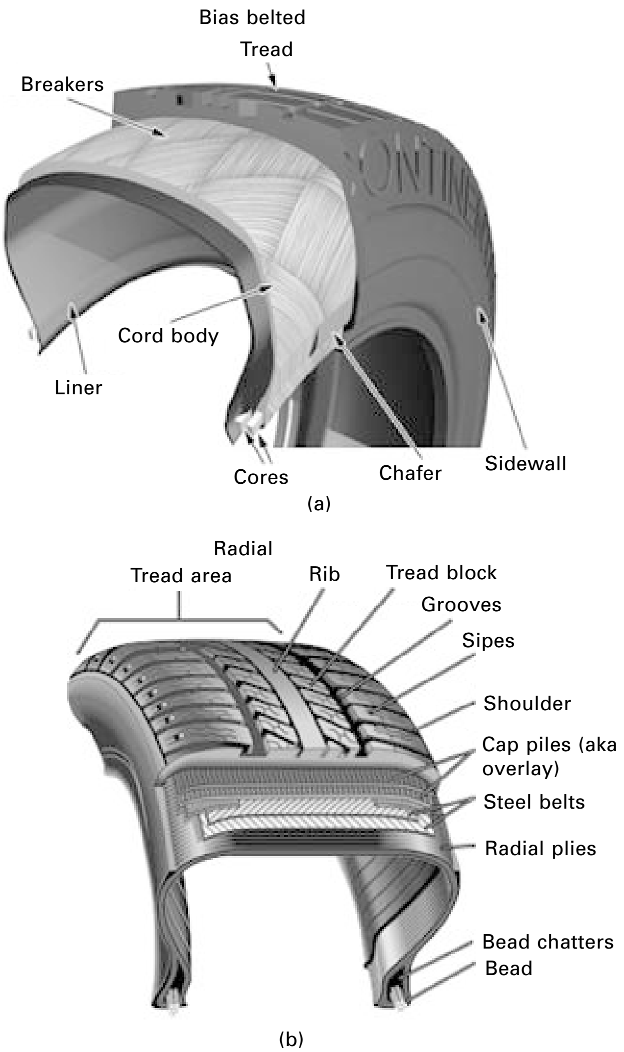
13.5 Automotive tire performance characteristics.[2]

characterization matrix is dependent on the end-use requirements for the tire. These characterizations have evolved over the past 100+ years and are designed to simulate end-use conditions. The top, generalized tire performance areas today are: reduced fuel consumption, increased load-carrying capabilities, better durability and retreadability, increased tread wear, improved ride and handling, increased traction, and lower noise.

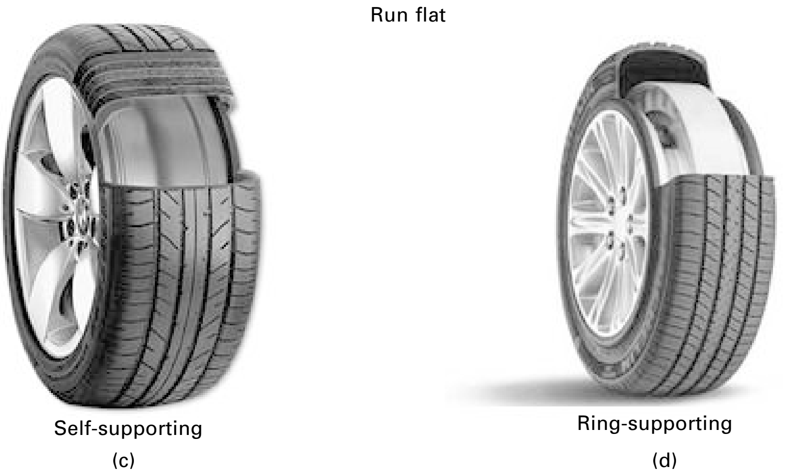
13.2.2 Tire designs in use today

In the automotive vehicle market, there are three types of unique automotive tire designs in use today: bias belted, run flat, and radial (Fig. 13.6). Bias belted tires are named after the two or more carcass plies which cross at a bias angle to the centerline of the tread.[7] Bias belted tires usually have a rounded tread face which increases tread wear and hence shortens the in-service tire life. Bias belted tires are one of the more durable tire designs due to the ability of the bias-angled carcass to help absorb most impacts through pantographing. Nowadays, bias belted automotive tires are typically used in areas where the road infrastructure is more demanding or for some specialty applications such as antique cars.

The run flat tire (either self-supporting or ring-supported design) represents the latest commercialized automotive tire design. The self-supporting tire is designed to minimally deflect (upon air loss) through the inclusion of stiff, sidewall inserts. The ring-supported tire is also designed to minimally deflect with air loss by contacting the tire onto a structural insert component which is attached to the inside of the rim. Each run flat tire design offer features that provide continued mobility in the event of an air-loss for a specified period of kilometers at a given maximum rate of speed.



13.6 Common automotive tire designs. Sources: http://www.carbibles.com/tyre_bible.html; http://discounttire.com/dtcs/infoTireConstruction.dos; http://www.familycar.com/CarCare/RunFlatTires.htm; http://www.aaa-calif.com/westways/0706/features/running-on-empty.aspy).

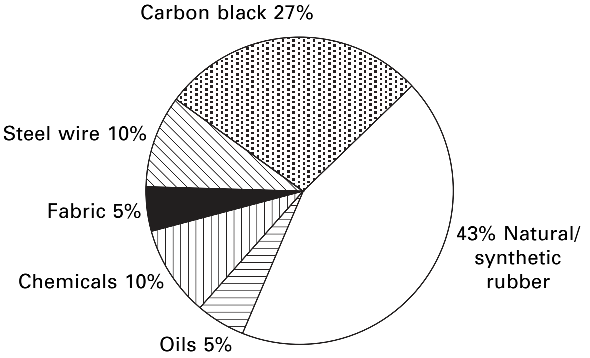


13.6 (Continued)

The radial tire is by far the most prevalent and broadly applied design in the automotive arena with over 1,000 MM units sold annually.[8] The radial tire[9] gets its name from the direction that the carcass plies run; i.e. radially across the tire, perpendicular to the beads. Radial tires have multiple belt plies at opposing angles (typically made-up of steel cords) which run circumferentially around the tire, under the tread, to stabilize the tread area. This additional restriction also increases the tread life (over the bias/belted tire design) through reducing squirm and friction with the road surface. The radial automotive pneumatic tire was first introduced by Michelin in 1949[10] but didn't get broad acceptance until decades later.

The typical automotive radial tire is composed of approximately 18 individual components, at least 12 different elastomeric-based compounds, 1 or 2 plies of fabric, two steel belts, and a bead.[11] Approximate compositions by weight can be seen in Fig. 13.7. While the typical automotive tire uses minimal amounts of textile reinforcements (i.e. ~5 wt%), their contribution towards the overall tire performance and behavior can be significant. In general, the automotive tire is a composite of relatively low strength, high extensible elastomeric matrix and a high strength, low extensible reinforcements. Primarily, the reinforcements give the tire shape, overall size, stability, and load carrying capability. To a lesser extent, the reinforcements can also impact ride, handling, noise, tread wear and vehicle fuel economy.

General cord properties are strength, toughness, dimensional stability, modulus and linear density (i.e. mass). Figure 13.8 compares/contrasts the most commonly used reinforcing fibers for some of these key properties (normalized for equivalent cord structure). The fiber/cord selected, for each tire type and tire component, is dependent on these properties coupled with

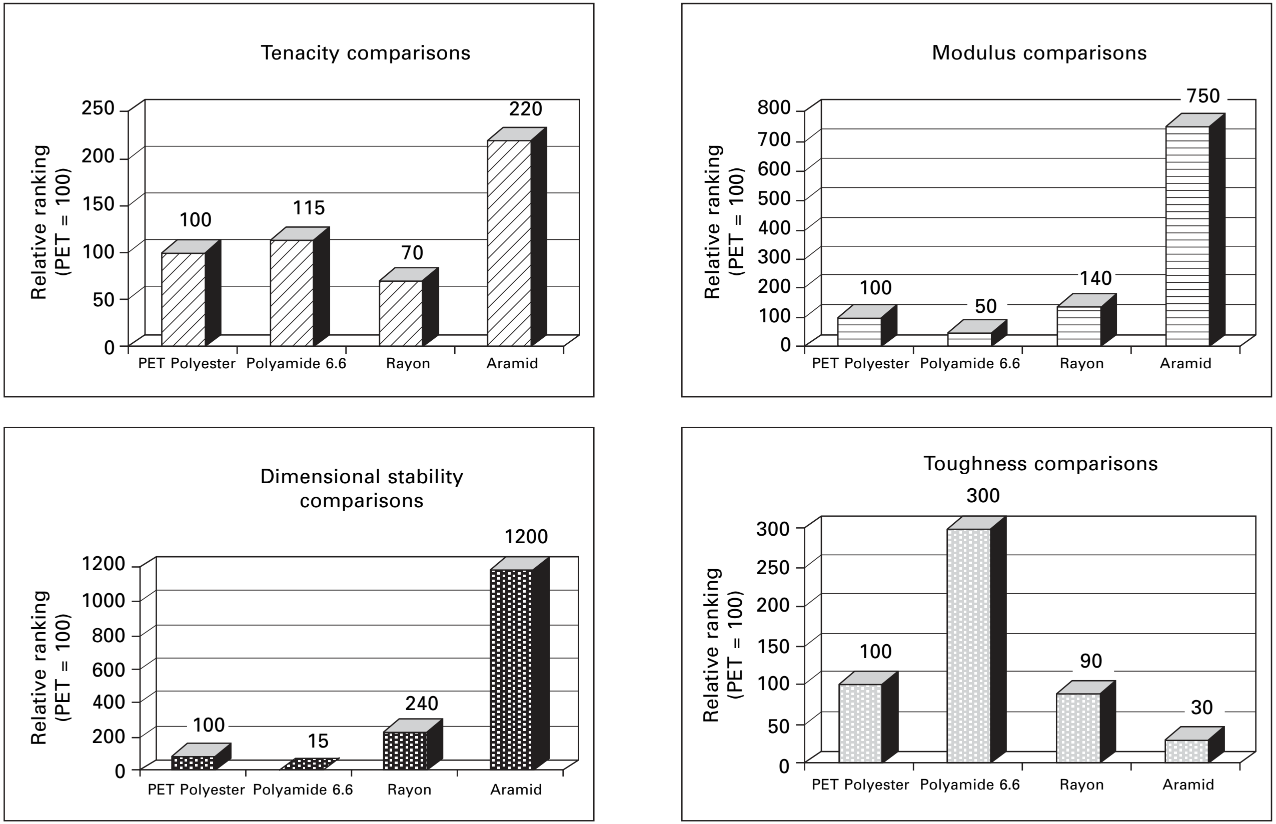


13.7 Typical automotive tire compositional breakdown (by weight).[10]

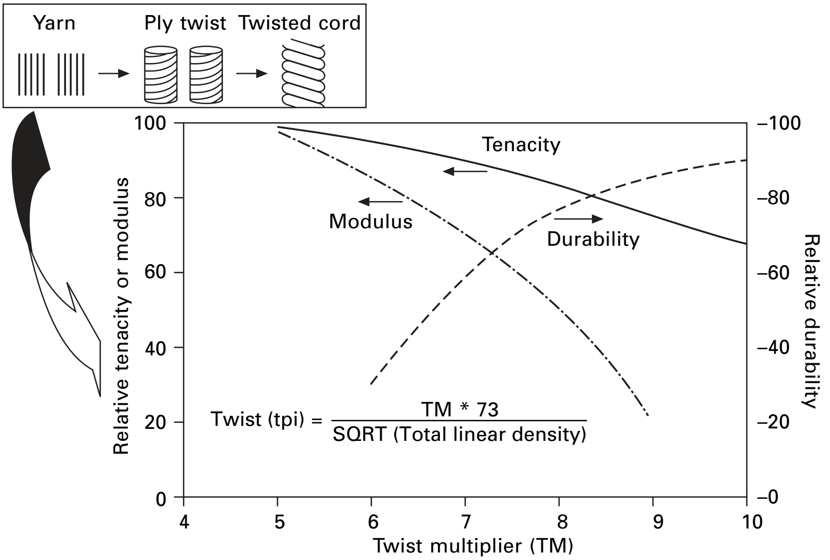
additional design considerations such as: the fibers' tensile and/or bending stiffness, thermal/chemical/mechanical stability, hysteretic behavior, cord structure, surface reactivity (e.g., for adhesion), end-use requirements and performance characterisitics. In most cases, the use of a textile-grade fiber is inadequate for tires. It is common to better describe the reinforcement fibers, used in tires, as industrial fibers. Industrial fibers generally offer significant physical property and chemical resistance enhancements over standard textile-grade fibers. In the tire industry, most fibers are used in the form of a twisted-cord. A twisted-cord structure can readily be varied to provide a wide range of properties desirable for in-tire use (Fig. 13.9).

Textile-based cords, in the automotive tire today, are most commonly used as the carcass (aka ply) reinforcement. Depending on tire design and usage, textile cords may also be used as flipper/chipper, overlay (aka cap ply) and toeguard (Fig. 13.10). The carcass (aka plies) is a highly engineered, twisted-cord structure made from PET polyester (predominately) or viscose cellulose (aka rayon). They are placed radially from bead-to-bead and are the primary reinforcing and strength member of the tire. Chippers and/or flippers are typically made from polyamide 6.6 or aramid fibers, twisted and woven into a uni- or multi-directional (e.g., square woven) structure and placed in the lower sidewall of the tire at a 30° to 65° angle (relative to the carcass angle). They provide additional composite stiffness in the lower bead-area to increase handling, help absorb deflection, reduce rim chaffing, and provide fretting protection between the steel bead and the carcass components. The overlay is made up of a series of unidirectional oriented twisted cords that run circumferentially around the tire, on top of the steel belts. They are used to enhance tire performance particularly for high speed applications. The most commonly used fiber type is polyamide 6.6, while aramid is also used especially in ultra high performance tires.

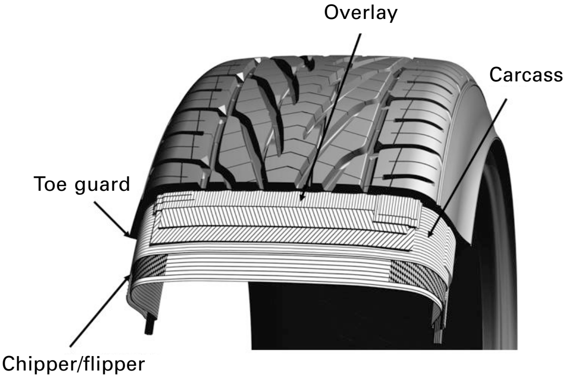
Pneumatic tires have undergone continuous evolution for the past 100



13.8 Relative property rankings (normalized for structure).



13.9 Cord properties as a function of twist level.



13.10 Textile-based reinforcement areas sometimes used in automotive tires.

years. Although the tire for the most part consists of rubber, the reinforcing materials do play critical roles in the overall tire performance. Today's tire reinforcement requirements are varied and demanding giving the designer/engineer an array of options and combinations to be used to enhance tire performance. Lighter weight materials, improvements in rolling resistance, uniformity and toughness continue to provide significant technological challenges.

13.3 Recent developments in fiber/textile reinforcements used in tire manufacturing

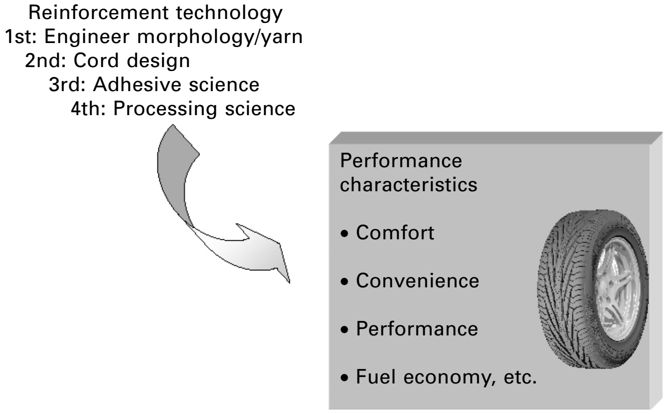
13.3.1 Basic research and development steps for fiber commercialization in tires

Fibers are the main reinforcing elements in the tire and provide a critical role in overall tire performance. Hence, it is no surprise that bringing a new fiber into the tire design is somewhat of a daunting task.

There are four basic research and development steps that must first be accomplished prior to fiber commercialization in tires (Fig. 13.11):

1. Engineered morphology – modify the fiber's structure to withstand the thermal/chemical exposure seen during the tire manufacturing and over its operational life.
2. Cord design – depending on the targeted tire component application, the textile fibers typically are formed into a cord structure to optimize strength, modulus, and fatigue resistance.
3. Adhesive science – a designed adhesive chemistry is used for each fiber type providing chemical and mechanical bonding to both the fiber/cord surface and surrounding matrix (i.e. rubber).
4. Processing science – where the reinforcement is subjected to elevated temperatures and tensions over a specified amount of time to stabilize the material for subsequent plant processing. This process, while both time consuming and costly, is necessary for the successful translation of intrinsic fiber properties and behaviors into positive "in tire" responsive characteristics.

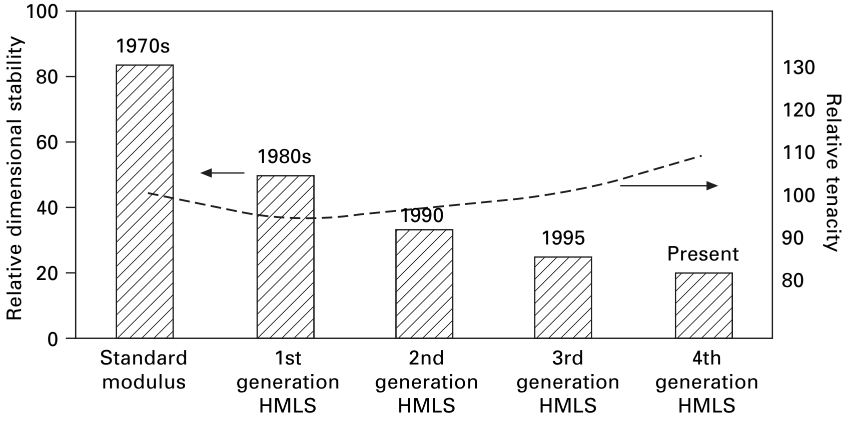
Key fiber physical properties, for use in tires, include: linear density, flexibility, and modulus (Table 13.1). These properties, along with structural



13.11 Tire reinforcement development methodology.

Table 13.1 Key intrinsic fiber properties for in-tire use

Linear density	Flexibility	Initial modulus	Specific tensile stress
$\lambda = \rho A_f$	Flexibility = $[EI]^{-1}$	$E = \frac{d\sigma}{d\varepsilon}\Bigr\rvert_{\varepsilon=0}$	STS = σ/ρ
where:	where:	where:	where:
λ = linear density	E = initial modulus	σ = stress	ρ = mass density
ρ = mass density	I = moment of inertia	ε = strain	σ = stress
f = fiber length			



13.12 PET polyester tire yarn development history.

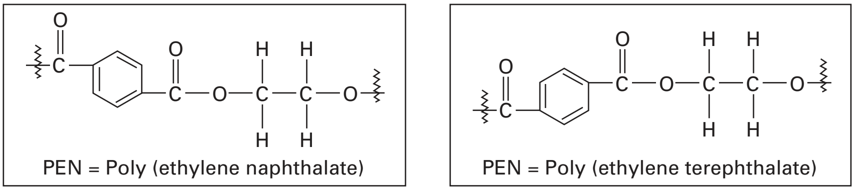
(e.g., Tm, Tg, MW), morphological (e.g., crystallinity, amorphous orientation), and thermal/chemical/dimensional (e.g., creep, modulus response, contraction) characteristics, are used to guide the designer in fiber selection and subsequent structural optimization to address a specific characteristic by targeting a specific tire component. These newly designed components are then encompassed into the overall tire design and optimized for specific tire performance characteristics.

13.3.2 Recent fiber and cord developments

Market demands for increased raw materials and technological advancements (mainly in processing) have been the main drivers for R&D of tire reinforcement materials. Throughout the 1970s, 1980s, and 1990s, advancements in tire reinforcement technologies could be easily described as derivative; that is to say, incremental physical property improvements in the areas of steel cord, polyester, polyamide 6 & 66, rayon and aramid.

As an example, Fig. 13.12 depicts the technology advancements of PET polyester over the past 20 years. PET polyester fiber development mainly focused on improvements in dimensional stability. Dimensional stability, measured in terms of shrinkage, creep, modulus retention, etc., is a measure of reinforcement's ability to maintain its physical properties and dimensions when subjected to an elevated temperature environment (e.g., tire cure, operating conditions). PET polyester fiber improvements advanced from standard modulus to 1st generation high modulus/low shrink (i.e. HMLS (higher modules, lower shrinkage), invented by Celanese[12] in the late 1970s) to the current 4th generation HMLS. These advancements have greatly improved tire uniformity (e.g., tire growth, appearance, sidewall indentations, and vibrations) and streamlined the tire manufacturing process by helping to reduce the need for a post-cure inflation (PCI) process. As an added benefit, fiber manufacturers' productivity level was also greatly increased thus reducing fiber manufacturing costs.

More recent polyester advancements have been in the form of new polyester derivatives; for example PEN (Fig. 13.13). PEN (poly 2,6 ethylene naphthalate) offers additional enhancements in dimensional stability (e.g., higher modulus, lower shrinkage) over PET. Intrinsically, PEN vs. PET offers not only higher dimensional stability but also higher Tg (glass transition temperature) and Tm (melt temperature) which can lead to additional benefits in manufacturing as well as in-service performance. Commercialized by several companies (e.g., Performance Fibers, Teijin, Invista and Hyosung), PEN[13] polyester fiber has seen limited success in tires. In 2004, Pirelli commercially introduced PEN as the carcass reinforcement for their new Dragon SuperCorsa PRO motorcycle tire.[14] There, PEN offers reduced in-tire weight for improved handling with excellent response and control. In 2006, Sumitomo Rubber introduced a tire with PEN[15] as the overlay component providing improvements in tire flat spotting and reduced tire noise. The significantly higher modulus



PEN = Poly (ethylene naphthalate)

PEN = Poly (ethylene terephthalate)

Intrinsic properties:	PEN	PET
Melt point, °C	268	250
Tg, °C	125	80
Specific gravity, g/cc	1.3–1.4	1.3–1.4

13.13 PEN vs. PET structure and intrinsic property comparisons. (Sources: http://www.bp.com/liveassets/bp_interest/globalbp/STAGING/global_assets/downloads/pdfs/acetyls_pta/N_17_PEN_Homopolymer_Prep.pdf; http://www.azom.com/details.asp?ArticleID=1933, ArticleID=2047).

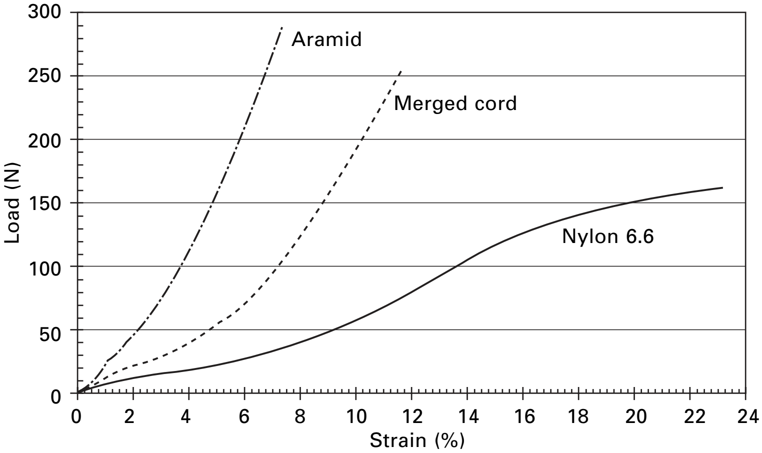
of PEN vs. conventional polyamide 6.6, helped to reduce tire vibrations under dynamic operating conditions.

Towards the end of the 1990s, new aramid tire yarns, offering enhanced properties, were being developed by both E.I. du Pont de Nemours and Teijin (formally known as Akzo Nobel).[16] In the mid 1990s, Dunlop[17] introduced an ultra light weight passenger tire (Dunlop SP Sport 200 ULW) that was manufactured with all aramid reinforcements: belts, carcass and beads. The significant weight reduction translated into improved fuel economy and reduced wear. However the tire's unique structural components and its low benefit/cost ratio did not resonate well with consumers during this time frame.

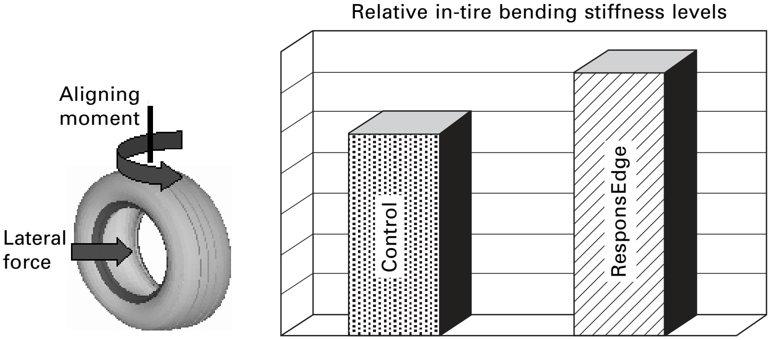
In 2004, Kumho[18] pioneered the use of Lyocell as a new carcass reinforcement material in their ultra high performance tire line called ECSTA. Lyocell fiber, a subclass of rayon, is commercially manufactured by Hyosung Corporation. Lyocell fibers offer similar in-tire responsive characteristics as viscose-based rayon. However, Lyocell is considered more environmentally green than viscose rayon because the manufacturing process is considered more environmentally friendly (e.g. reduced effluents, less harmful solvents).

In 2005, The Goodyear Tire & Rubber Company introduced a new line of radial light truck tires called "Silent Armor™" that featured DuPont's Kevlar® in a merge/hybrid cord structure.[19] The cord structure was engineered to provide additional modulus and stiffness for enhanced tire performance while significantly reducing the tire noise level. Later that same year, a similar merge cord construction was launched by Goodyear in Europe for the ultra high performance passenger tire market. The merge/hybrid cord structure concept enables one to optimize reinforcement properties using two or more dissimilar fiber types. The addition of Kevlar® to a polyamide 6.6 fiber (Fig. 13.14) produced a cord which has high toughness, mid-modulus level with moderate ductility. Also in 2005,[20] a new advanced polyester tire cord was introduced in on-highway radial light truck tires under the name Fortera Triple Tred®. The specialized polyester tire cord helps reduce flatspotting, while maintaining a smooth, comfortable ride. As one can see, there is no one catch-all approach that can satisfy all our customers' needs. Hence, the tire designer selects the best known combination of reinforcements, compounds and structural design to address each specific performance characteristic.

In 2006, The Goodyear Tire & Rubber Company introduced the incorporation of carbon fiber tire cord[21] as a chipper in a high performance passenger touring tire called Eagle ResponsEdge®. The carbon fiber chipper, placed along the lower bead area of the tire on the outboard side of the tire, offers enhanced sidewall stiffness when needed (e.g., during an evasive maneuver) without sacrificing ride and comfort (Fig. 13.15). Carbon fiber's high stiffness/weight ratio was the key intrinsic property used to achieve the desired tire response without adversely impacting tire balance and inducing non-uniformities (e.g., vibrations).



13.14 Tire cord's deformational response when subjected to an applied axial strain.



13.15 In-tire stiffness comparisons.

In 2007, The Goodyear Tire & Rubber Company introduced carbon fiber micro-technology in an ultra high performance passenger tire called Eagle® F1 All Season.[22] The addition of micro-carbon fibers, in both inner and outer lower sidewalls, further enhanced the tire's handling characteristics through increasing sidewall stiffness (tension, torsion) without compromising other tire performance characteristics.

Recent advancements in reinforcement technology have enabled tire companies to further enhance tire performance characteristics. In addition, these new reinforcements have enabled tire producers to design highly engineered, highly tailored, and highly differentiated automotive tires that offer significant value to both the end-use consumer and manufacturer. Continued new and improved fiber technologies should result in further enhancing tire performances to meet the ever changing needs in the market place.

13.4 Fiber-rubber adhesion in tires

13.4.1 Bonding of fiber reinforcement to tire matrix

Bonding of continuous fiber reinforcements to the elastomers used to form the matrix of the tire requires the meshing of different chemistries to form a link stronger than the cohesive strength of the matrix. In the original pneumatic tires, where cotton duck fabric was used as the reinforcement, the mechanical bond of the rubber to the fabric was sufficient to exceed the relatively weak internal strength of the cotton staple fibers. With the introduction of continuous rayon fiber in the 1930s, the need for a fiber adhesive coating became apparent since the higher strength of rayon fiber shifted the focus area of improvement to the fiber/rubber interface.

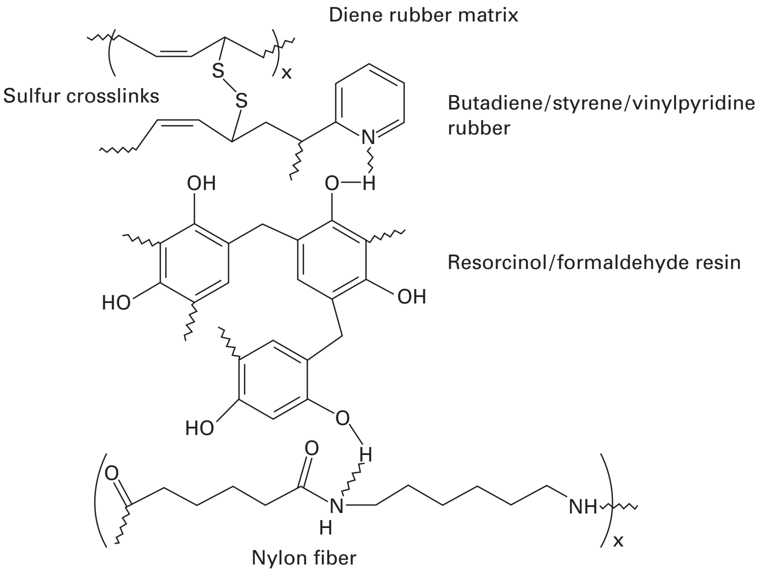
Early adhesives were based on naturally derived protein glues such as casein,[23] but these were quickly supplanted by synthetic phenolic resins, primarily based on the reaction of resorcinol with formaldehyde.[24] Resorcinol can be readily reacted with formaldehyde in aqueous solution at room temperature to form a three-dimensional resin network. Extensive studies were conducted to determine the optimum ratio of formaldehyde to resorcinol and the resin to rubber ratio to provide the proper balance of strength and flexibility.[25]

Natural rubber latex was used for fabric adhesives until the 1950s, when synthetic lattices became readily available. SBR latex was used at first, followed by the introduction of butadiene/styrene/vinylpyridine terpolymer (ASTM designation PSBR). Incorporation of vinylpyridine into the polymer structure results in much stronger bonding of the resin to the adhesive elastomer.[26] This became particularly important with the introduction of nylon 6 and 6.6 fibers for tire use. The higher internal strength of the adhesive and greater polymer functionality was well suited to the higher fiber strength and lower surface reactivity of nylon relative to rayon. PSBR quickly became the standard latex for tire cord adhesives and remains so today (Fig. 13.16).

Modification of the rubber matrix to promote fiber adhesion was also studied after the introduction of nylon fibers. Addition of silica, resorcinol, and a formaldehyde donor to the rubber compound was found to improve adhesion to nylon. The level of adhesion obtained and the change in compound properties caused by the high level of additives required have limited the utility of this approach for tire applications, although it has been widely used in mechanical rubber goods.[27]

13.4.2 Adhesion activation chemistry

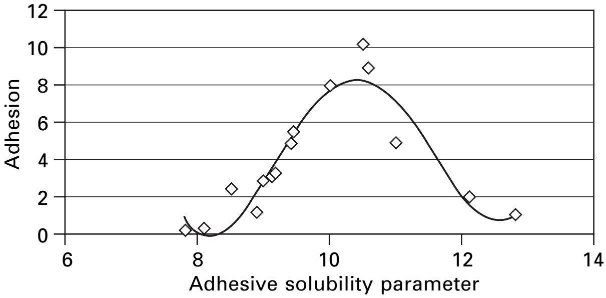
The development of polyethylene terephthalate (PET) polyester fiber for tire cord in the 1960s required new adhesive chemistry to match the level of adhesion obtained with resorcinol formaldehyde latex (RFL) adhesives on



13.16 Schematic of RFL (resorcinol formaldehyde latex) fiber to rubber bonding.

rayon and nylon. Polyester lacks the high wettability and reactive surface functionality of rayon and nylon. As a result, the simple RFL adhesives which worked well for the latter two fibers showed lower adhesion to polyester.[28] Various alternative chemistries were explored in an effort to increase polyester adhesion to rubber, including modification of the resorcinol resin to increase interaction with the fiber, use of solvent-based reactive resins to promote surface reactions, and increases in processing temperature to increase reaction rates. Theoretical studies by Iyengar at Dupont demonstrated that matching the solubility parameter of the bonding resin to that of the fiber resulted in the highest level of adhesion and offered an explanation for the particular effectiveness of epoxy/isocyanate resin combinations in bonding to polyester[29] (Fig. 13.17).

The demand for improved polyester to rubber adhesion also led to the development of reactive sizings applied by the yarn manufacturers during spinning or drawing stages of the yarn.[30] The term “adhesive activation” was coined to distinguish such treatments from the standard spin finishes applied as lubricants to protect the fiber during subsequent mechanical operations such as twisting and weaving. Each manufacturer developed and in many cases patented their own chemistry for adhesive activation, with the result that performance can vary from one supplier’s yarn to another depending on the adhesive subsequently applied and the process conditions used. Modifications to adhesive activation chemistry continued into the 1990s to address toxic emissions and cord fatigue from filament fusion.



13.17 Adhesion of coatings to PET film vs. solubility parameter.

Another approach to improving polyester adhesion has been to modify the yarn composition. This can be accomplished in several ways, including bicomponent fibers, in which a core of PET is surrounded by a sheath of another polymer, polymer blends, and copolymers. Each of these alternatives presents a challenge to retain the desired yarn physical properties while enhancing surface adhesion. In practice such yarns have not found wide use in the tire industry because of unfavorable tradeoffs in either performance and/or price.

Fiberglass was introduced as a tire reinforcement in the 1970s for use in belts. A radically different process for adhesive coating was developed to deal with the surface chemistry and physical properties of glass cord. The yarn is treated with a functional silane and heat treated to bond it to the fiber surface.[31] The silane functionality is chosen to provide reactive groups suitable for interaction with RFL chemistry. The resulting treated yarn is then coated with a customized RFL adhesive in a process designed to provide complete penetration of the yarn bundle with the RFL. The dipped yarn is then twisted and woven into fabric. The RFL adhesive here serves as both a bonding agent and a protective coating to prevent damage to the brittle glass filaments.

Aromatic polyamide or aramid fibers were also introduced as tire cord reinforcements in the 1970s. Poly-p-phenylenediamine terephthalamide, produced commercially as Kevlar® by Dupont and Twaron® by Akzo (later Teijin), has seen the widest use in tires of this general class. At first examination it would seem that the RFL adhesives used successfully for nylon fibers should function well for bonding aramids, but this is not the case. Aramids differ from nylons in that they are fully crystalline and have little reactive functionality present on the outer surface of the cord. A variety of reactive chemicals have been used to bond to the fiber surface, followed by coating with an RFL adhesive to provide bonding to the rubber coat compound. High chemical reactivity to promote bonding has to be weighed against potential damage to the fiber and concomitant loss of tensile strength. Low molecular weight polyepoxides are most widely used for the initial adhesive coating.[32]

Adhesive activation coatings similar to those used in polyester have been developed and marketed, but increased yarn cost and limited availability has limited their use for tire cord.

Carbon fiber was proposed for tire cord use in the 1980s, but only recently has the "in-tire" value become favorable for its use. A reactive resin is applied by the fiber manufacturer to functionalize the relatively inert fiber surface. The sized yarn is then coated with RFL adhesive in a process similar to that used for fiberglass.[33] As with fiberglass, the adhesive serves a dual function as a bonding agent and a protective coating to prevent filament fretting.

Polyethylene naphthalate (PEN) polyester, although developed in the 1980s, did not become widely available commercially until the 1990s due to availability of the naphthalene diamine monomer. Bonding to PEN can be achieved with chemistry similar to that used for PET and relies on the same principle of mutual solubility of the adhesive resin and the fiber.

Many other fibers that have been proposed for tire use, including polyvinylalcohol (PVA), nylon 4.6, solvent spun cellulose (Lyocell), and polyolefin ketone (POK), have sufficient surface polarity and reactivity to bond well to conventional RFL adhesives. High strength crystalline fibers such as poly(bis)benzoxazole (PBO) typically require adhesive coatings similar to those used for aramids.

13.4.3 Alternatives to the classical resorcinol formaldehyde latex adhesives

Alternatives to the classical RFL adhesives for tire cords have been proposed, especially recently given the regulation of formaldehyde and resorcinol. Several commercial resin products have been marketed as resorcinol alternatives, including melamine resins[34] and naturally derived alkyl-resorcinols.[35] Formaldehyde alternatives that have been suggested include furfural and glyoxal, but both these aldehydes present issues similar to those associated with formaldehyde.

Radically different coating chemistries have also been studied. Elimination of the epoxy and isocyanates used for PET and aramid bonding has been proposed through the use of reactive surface treating, including low temperature vacuum plasma,[36] corona, ozone/UV, and fluorination. These methods are aimed at increasing the surface reactivity of the fibers through oxidation, so that the resulting hydroxyl, ketone, and carboxylic acid groups are available for bonding to RFL adhesives. The resulting fiber surface then exhibits reactivity similar to rayon. Direct bonding of fibers to rubber elastomers has also been attempted through the use of surface grafting. In this case reactive monomers are polymerized onto the fiber surface after activation by strong base, electron beam, or plasma treatment.

13.5 Recent advances in tire designs

13.5.1 Self-supporting run flat tires

Continual advancement in tire designs has enabled tire manufactures to not only incorporate new materials but to take full advantage of their intrinsic characteristics and optimize the translation into tire performance characteristics. The majority of these advancements involved new polymers, fillers (like silica), oils, etc., coupled with new tread/sidewall designs and overall tire contour shapes. New fiber reinforcement materials have historically played a smaller role in these developments due in part to the role each reinforced component plays in maintaining the tire's overall performance. However, as discussed earlier, new fibers/structures are becoming more and more important in meeting these tire performance needs.

In 1978, The Goodyear Tire & Rubber Company developed the industry's first self-supporting run flat tire at the New York auto show.[37] First commercialized for Chevrolet Corvette, the self-supporting tire design (now called RunOnFlat™) is built to maintain its shape and driveability even after losing all the air pressure through incorporation of special reinforced-rubber inserts in the sidewall. When a standard tire deflates, it simply collapses under the weight of the vehicle, allowing the beads to be unseated and the sidewalls to be in contact with the rim. Within a very short distance, the tire quickly reaches its end of serviceability. The reinforced sidewalls in the Goodyear RunOnFlat™ tire keeps the tire on the rim and carries the vehicle load for up to 80 km @88 km/hr after a complete air-loss event. The RunOnFlat™ tire operates almost undetectably when flat and hence must be fitted with a pressure monitoring system to alert the driver when air loss occurs. Currently fitted on many high performance vehicles all over the world, the RunOnFlat™ tire also offers many benefits including: piece of mind, continued mobility, space savings, and convenience. Additional tire manufacturers have designed similar run flat technologies including: Dunlop DSST, Michelin ZP, Bridgestone RFT, Pirelli EUFORIA, and Continental SSR.

13.5.2 Modular tire manufacturing

In the late 1980s, Michelin introduced a radically new kind of tire building process called C3M (Carcass, Monofil, Moulage, Mechanique).[38] The C3M process is a modular, custom designed process that enhances accuracy for the placement of multiple components during tire manufacturing. The overall footprint of a C3M machine (tire building/curing module) would fit comfortably in a standard commercial trailer vs. today's tire plants that encompass many acres. The C3M is not specifically engineered to be a cost saving process, but instead to maximize manufacturing flexibility in the form of short production runs of specialized tire orders (e.g., Scorcher T/A's) and OE-quality ultra high performance and SUV tires. In addition, C3M provides the flexibility of physically placing the equipment virtually anywhere in the world. Michelin has already placed 15 million original equipment and replacement C3M-made tires on the road since 1997 (e.g., Pilot Sport A/S Ultra-High Performance All-Season tire) while the others are still in the pre-mass market stages. Goodyear (IMPACT), Pirelli (MIRS), Bridgestone (ATMSS), and Continental (MMP) have also developed or are developing modular tire manufacturing systems.

13.5.3 Ring-supported run flat tire

Ca. 1996,[39] Michelin introduced a ring-supported run flat technology system called PAX®. Requiring a special wheel and a polyurethane inset to function, the PAX® is designed to keep the tire on the rim even if all the air is removed. With the loss of air, the tire collapses on the insert and thus preventing the sidewalls from coming in contact with the rim. Fully inflated, the PAX® tire offers similar performance features as the conventional pneumatic radial tire (e.g., ride, handling, fuel economy) due in part to the compliant sidewall design. Under a total air-loss condition, the PAX® tire design enables the operator to continuing traveling at 55 mph for up to 125 miles. The Michelin PAX® tire was first fitted on the 2001 Renault Scenic automobile. Since then, O.E. fitments have grown and now include Audi A6 Quattro and upcoming Honda and Nissan models. In addition to Michelin, Continental, Pirelli, Goodyear and Sumitomo have also been engaged in the development of a PAX® tire system.

13.5.4 "Self-sealing" run flat tires

Another form of run flat tire is the "self-sealing" type which came on the scene in the 1970s. These tires are specially designed with an extra lining (located inside the tire) which contains a pre-described amount of puncture sealant polymer. Upon puncturing, the sealant flows around the penetrating object, helping to minimize the loss of air. If the object fully penetrates the cavity, the void is filled by the same sealant polymer. This technology is very effective for small objects such as nails, bolts or screws up to ~3/16″ in diameter in the repairable area of the tread. Uniroyal (Tiger Paw NailGard) and Continental (AST Self-Sealing) both manufacture tires to this market segment.

Run flat tire summary

The use of run flat tires has been most successful in high-end "niche" applications like ultra high performance vehicles and mini-vans. All of the major tire companies, including Goodyear, Bridgestone/Firestone, Michelin, Continental, and Pirelli offer one or more run flat tire designs. To date, no one design will satisfy all customer requirements. Some automotive vehicles come fitted with run flat tires including: BMW Mini Cooper S, Chevrolet Corvette, Lexus SC430. BMW has stated plans to make run flat tires standard equipment on all its models in the very near future. Despite their success, run flat tires still need to address additional hurdles[40] before becoming more broadly accepted. These hurdles include further improvements in ride and comfort (especially for self-supporting designs), uniformity (primarily self-sealing tires), reduced weight, increased fuel economy, increased tire size selection, fitment on conventional wheels (notably ring-supported designs), and reduced costs.

13.5.5 Multiple tread-zone tires

In 2004, The Goodyear Tire & Rubber Company introduced a new, broad market automotive tire design called Assurance® Triple Tred,[41] featuring three distinct tread zones. The Assurance® tire's three tread zones help provide continual performance when subjected to dry, wet or icy conditions. The ice zone incorporates small amounts of fiberglass in the compound providing added grip and traction. Many other tire companies have followed suit with similar features that provide enhanced tire performance under various road surface and environmental conditions.

13.5.6 Pneumatic and non-pneumatic polyurethane tires

In 2003, Amerityre announced its Arcus™ pneumatic passenger car tire concept.[42] The tire uses conventional reinforcement materials and incorporated their proprietary polyurethane elastomer technology. By November 2007, Arcus™ successfully completed testing to meet USA Federal Motor Safety Vehicle Standards (FMVSS) 109 and 139. Arcus™ is said to offer (among other things) longer life and lower rolling resistance (resulting in improved fuel economy) than conventional rubber pneumatic tires. Amerityre also offers a wide range of other polyurethane-based tires including: non-pneumatic low speed foam tires called Flatfree™ (e.g., bicycles and golf carts), composite tires (e.g., polyurethane treads on conventional rubber tires), and solid tires (e.g., fork trucks).

13.5.7 Integrated tire and rim non-pneumatic tire

The latest new automotive tire design announced is the Michelin "Tweel" concept.[43] The heart of Michelin's Tweel innovation is its deceptively simple looking hub and spoke design that replaces the need for air pressure while delivering performance previously only available from pneumatic tires. The flexible spokes are fused with a flexible wheel that deforms to absorb shock and rebound with unimaginable ease. Without the air needed by conventional tires, Tweel still delivers pneumatic-like performance in weight-carrying capacity, ride comfort, and the ability to "envelope" road hazards. Michelin has also found that it can tune Tweel performances independently of each other, which is a significant change from conventional tires. This means that vertical stiffness (which primarily affects ride comfort) and lateral stiffness (which affects handling and cornering) can both be optimized, pushing the performance envelope in these applications and enabling new performances not possible for current inflated tires. The Tweel prototype, demonstrated on the Audi A4, is within five percent of the rolling resistance and mass levels of current pneumatic tires. That translates to within one percent of the fuel economy of the OE fitment. Additionally, Michelin has increased the lateral stiffness by a factor of five, making the prototype unusually responsive in its handling. Commercially unavailable at the moment, the Michelin Tweel as well as similar air-less automotive tire technologies will not be available to the general public for several years.

13.6 Future trends

One could ask "What drives the future?" The answer is many things: demographics, natural resources and the environment, the global economy and globalization, national and international governance, future conflicts, and last, but certainly not least, science and technology. No single driver will dominate. Each will have varying impacts in different regions. They are not necessarily mutually reinforcing. So how are they going to impact the transportation business? More directly, how are they going to impact automotive vehicles of the future? How will the future automotive vehicles impact future tire needs including materials, reinforcements, and designs?

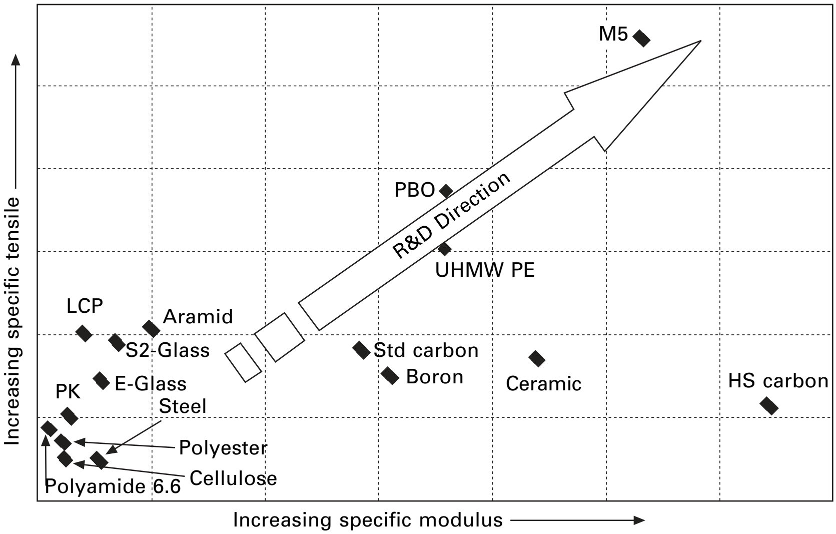
For the automotive markets, one can visualize convergence of several technologies including wireless, nano and sensors. These technologies should converge and create embedded connectivity, robotic-like behaviors, 3D video projections and interactive holography all in the name of improving vehicle capabilities, passenger comfort and convenience. Future vehicles look to be smaller, use alternative fuels (e.g., hydrogen, electricity), and carry higher loads coupled with higher fuel efficiency.

As for tires, our requirements will continue in the path already in progress. In the near term, demand will continue to increase primarily driven by significant growth in China, India, and Eastern Europe. Increase in tire size and complexity will help advance the need for additional modular tire building manufacturing like Michelin's C3M or Goodyear's IMPACT.

In the longer term, significant reduced tire weight (approaching 50%+ lower) will become a necessity in order to achieve the fuel economy needed for the most advanced automotive vehicles. In helping to achieve these needs, new, advanced materials and fibers will be discovered and incorporated into new tire designs to not only achieve the advanced performance requirements imposed, but to make the tire more ecologically friendly through the incorporation of more evergreen, non-petroleum based materials.

Future reinforcement opportunities for tires (especially automotive tires) remain positive. Driven by customer needs, the general fiber industry trends can be seen in Fig. 13.18. Higher modulus and higher strength materials are where all the activities are. Key market drivers are aerospace, military and ecology which will place huge pressure to further advance fiber properties as well as to make them more bio-friendly. Smart/responsive materials, at all levels including macro, micro and nano, will be incorporated into tires making them intelligent and auto-responsive to the changing environment. Novel reinforcement materials and structures will be discovered to protect tires from environmental hazards and improve tire life.

New fibers on the horizon are many and varied. Some will be directly applicable to tires, while others may require novel approaches to best take advantages of their features. Fibers such as polyvinyl alcohol, polyamide 4.6, poly(diimidaza) pyridinylene (dihydroxy) phenylene (aka PIPD or M5), polyethylene ketone, poly p-phenylene benzobisoxazole (PBO) and the like offer enhanced features that will require advanced tire designs and knowledge to be incorporated as a structural member in the tire. Other fibers such as nanocomposite and spider silk offer potential for extreme advancements in



13.18 New fiber technology R&D path.

tire reinforcement science and design. Still other bio-fibers such as bamboo, polylactic acid, hemp, etc., may offer surprises in advancing the reinforcement capabilities of elastomeric matrix under both static and dynamic conditions. In addition, the expansion of composite-like cord structures (e.g., merging two or more dissimilar fibers into one cord structure, core-sheath fibers) will offer unique reinforcing behaviors for maximizing "in-tire" value.

In summary, today's tire reinforcement fiber requirements are varied and demanding. Lighter weight materials, improvements in rolling resistance and uniformity along with increased toughness continue to place significant technological challenges. New emerging fibers, while not initially designed for tires, offer significant potential to address these challenges and provide further options to tire designers. Methodologies for the development of new fiber reinforcement materials must include cure/production and in-service/dynamic composite simulations to fully assess and maximize "in tire" performance and value.

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