Polycarbonate (PC)

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The consumption of polycarbonate has enjoyed continuous, above-average growth since the "invention" of this material nearly 50 years ago, attributable in no small part to the discovery of an ever-increasing number of applications for it. This development will continue, so that, after a brief period of stagnation due to the sluggish economy, demand is likely to pick up again in 2002.

For the majority of its varied applications, polycarbonate's key property is its glass-like transparency due to its amorphous structure. In combination with high heat resistance, excellent toughness and outstanding dimensional stability, it has a unique range of properties. Its property profile is rounded off by good electrical insulating capacity, sterilisability and suitability as a blend partner, constantly opening up additional new fields of application.

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Worldwide demand for plastics rose in 2001 to a total of 173 million t (Fig. 1). The majority of this consisted of standard thermoplastics, while engineering thermoplastics accounted for around 7 % or 12 million t. In the field of engineering thermoplastics, polycarbonate is playing an ever more important role, both as a straight polymer and as a blend partner. In volume terms, it occupies second place behind ABS and ASA and ahead of PMMA, PA 6 and PA 66 (Fig. 2). Ever since the almost simultaneous discovery of polycarbonate in the laboratories of Bayer AG and General Electric in 1953, PC has developed continuously with an average annual growth rate of around 10 %, and, particularly since the end of the eighties, has enjoyed significantly higher growth than other engineering plastics.

Market Situation

From 1990 to 2001, global PC consumption more than trebled – from 610 000 t to 1 900 000 t (including 300 000 t for PC in blends) in 2001 (Fig. 3). This demand compares with a nominal capacity in 2001 of around 2.4 million t, so that real output was able to fully cover market demand. However, through the sudden increase in demand for optical data carriers (CD-R),

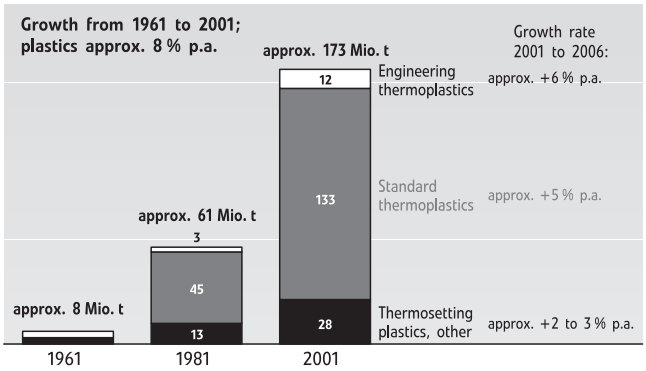
delivery bottlenecks occurred in 2000, and although consumption in 2001 stagnated because of the slowing down in the global economy, demand is expected to rise again in 2002. In order to achieve a balanced relationship between supply and demand, it will be necessary to raise global PC capacity continuously by 8–10% p.a. For this reason, the manufacturers are consistently expanding their worldwide capacities. In volume terms, the Asian region clearly dominates with over 40 % of the world PC market. Here, the demand for polycarbonate has doubled in the last six years. North America and Europe are some way behind in second and third places (Fig. 4).

In terms of tonnage, Bayer and GE Plastics are the world's leading manufacturers of polycarbonate, having together supplied around 65% of the global nominal capacity in 2001. Dow had somewhat more than 10 % of the capacity and the Japanese producers, Teijin, Mitsubishi and Idemitsu together contributed approx. 20% of world capacity (Table 1).

To accompany the above-average growth in the Far East, new PC production sites have been built in Asia over the last few years. In Thailand, for example, Bayer put a 50000 t polycarbonate plant on stream in 1999 and expanded its capacity at the beginning of 2002 to 150000 t. Mitsubishi, together with the TOA Group, operates a 60000 t PC line, also in Thailand, Teijin produces approx. 130000 t polycarbonate at a new site in Singapore, and Dow, together with LG Chemical, started up a 65000 t PC facility in Korea in 2001. Formosa/Idemitsu and Chi Mei/Asahi have announced that they will begin producing PC in Taiwan during 2002. In addition, Bayer, GE Plastics and Dow will be extending their main production sites further to provide the necessary capacities to meet the forecast market growth of around 9% p. a. (Table 2, Fig. 4).

Process Developments

Some 90 % of the polycarbonate is nowadays produced by the traditional two-phase interfacial process. The first commercial PC facility that went on stream at Bayer in Krefeld/Germany in 1958 produced polycarbonate by the melt transesterification process, which involved reacting bisphenol A with diphenyl carbonate (DPC) to produce melt polycarbonate (MPC). To obtain the raw material, dimethyl carbonate was first produced from methanol and carbon monoxide, and then reacted with phenol in a second reaction stage to produce the diphenyl carbonate. In the 1990s, the melt transesterification process gained increasing popularity. In 2000, Bayer put a 40000 t MPC line on stream in Belgium and is planning to start up MPC production in Caojing/China in 2005. GE Plastics manufactures PC by the MPC process in Japan and Spain.



*) without synthetic fibres, including coatings, glues, dispersions

Fig. 1. Global demand for plastics

Applications and Consumption

Optical Storage Media: The fastest growing field of application for PC is that of optical storage media. Development in the last few years has been nothing short of amazing. Global PC demand for optical storage media rose from 100000 t in 1995 to 430000 t in 2001 – a more than fourfold increase. It represents a share of 22 % of worldwide PC sales (Table 3). As these high growth rates are expected to continue, demand in this segment alone is likely to double by 2005 to around 800000 t/a. Although only minor growth rates are expected for audio CDs and CD-ROMs, the main growth driver will in future be the CD-R and above all the various DVD formats. The number of DVD videos sold in Germany alone, for example, increased by more than 600 % from 1999 to 2001. DVDs, which look the same as CDs, have several times the storage capacity. While a typical audio CD has a capacity of 650 MB, between 4.7 and 18 GB of data can be accommodated on a DVD, depending on the type. OBCs (Optical Business Cards) are an interesting new application with 20 to 100 MB of storage capacity in card format. They provide information on business-related data and can be read in standard drives.

The increase in storage density is being accompanied by constantly rising demands on the quality of the PC. Without specific product development, progress would be impossible. For this reason, special polycarbonates have been developed which have not only excellent processing characteristics but also attractive mechanical properties. Bayer, for example, manufactures a tailor-made product for the production of optical storage media in which the surface structures (pits) are optimally reproduced with cycle times of less than 5 s. In CD production, cycle times of just under 3 s have nowadays become the norm (Fig. 5). Subsequent generations of optical storage media (DVD-R) that have an even more highly compressed information density and use lasers with an even shorter wavelength will also use polycarbonate as the substrate material.

Construction: Due to PC's excellent combination of properties such as transparency, mechanical resistance, dimensional stability and good extrudability, it is the ideal material for the production of sheets and profiles. Ever since PC sheet was launched onto the market in the 1970s, this application has grown at a very satisfactory rate and, by 2001, global demand had reached more than 300000 t. As far as the future is concerned, PC manufacturers expect a lively growth of around 8 % p.a. By the year 2006, demand is thus expected to have grown to around 450000 t. The global PC sheet market is divided into solid sheeting, which accounts for 60 % (in terms of weight) and multi-wall sheeting with a share of 30 %. The remaining 10 % is made up of corrugated sheet and panels.

High performance, UV-stabilised products are available both for solid sheets and for corrugated sheets. These products have the necessary high viscosity and high melt stability that are needed for sheet extrusion.

Producer	Production site	Trade name
Bayer	Germany, Belgium, USA, Thailand, China*	Makrolon, Apec
GE Plastics	Netherlands, Spain, USA, Japan	Lexan PC
Dow Sumitomo Dow LG Dow	Germany, USA Japan Korea	} Calibre
Teijin	Japan, Singapore	Panlite
Mitsubishi Engineering Samyang Mitsubishi	Japan, Thailand Korea	Iupilon, Novarex, Kobaloy Trirex
Idemitsu	Japan	Taflon
Polycarbonatos do Brazil	Brazil	Durolon

* Due to go on stream in 2005, currently under construction

Table 1. Polycarbonate manufacturers worldwide in 2001

Multi-wall sheet is noted for its low unit weight and its flexibility and is used among other things for greenhouse roofs. The hollow structure reduces thermal conductivity and thus cuts heating costs in hothouses in winter. Multi-wall sheet and solid sheet of PC are now almost invariably given some form of UV protection by surface treatment – mostly by coextrusion or surface coating, depending on the sheet manufacturer.

Today, the two major PC raw material manufacturers, GE Plastics and Bayer, are largely forward-integrated in the sheet segment. Bayer, for example, is also globally positioned as a PC sheet manufacturer through its subsidiary companies, Sheffield (USA), Makroform (Europe) and Bayer Guyangi (China), Sewon (Korea) and Laserlite (Australia).

Electrical/Electronics: With a share of 28 %, the electrical/electronics sector is still the biggest application segment for polycarbonate in volume terms. The major strengths of PC for such applications are, in addition to its transparency, heat resistance and impact strength, its good electrical insulation properties (virtually independently of environmental influences), and outstanding dimensional stability. Typical applications include housings for distributing boxes and their covers, terminal strips and edge connectors, relays, safety switches, electricity meter housings, lighting covers and housings for household appliances. Numerous PC grades with specific property profiles have been developed to comply with the wide variety of different specifications.

Area of application	Volume share [%]
Electrical/Electronics	28
Construction	18
Optical storage media	22
Automotive	9
Packaging	3
Medical technology	3
PC blends	15
Others	2

Table 3. Polycarbonate applications by segment in 2001

Region	Growth [% p.a.]
Europe	approx. +8
North America	approx. +8
Japan	approx. +5
Rest of Far East	approx. +15
Rest of the world	approx. +8
World (average)	approx. +9

Table 2. Forecast regional growth rates for polycarbonate for the period 2001–2006

Use is made here almost exclusively of reinforced and fire-retardant products. PC has benefited considerably from the trend toward miniaturization and thin-wall technology: A few years ago, the first mobile phones weighed several kilograms, but a weight of less than 200 g is nowadays state-of-the-art for a modern cellular phone. Because the electrical performance has to remain the same or be even higher, the demands made on the material have also increased. Smaller, thinner components require materials with outstanding flow properties, good dimensional stability even at elevated temperatures and high impact strength at low wall thicknesses of 1.2 mm and less.

Packaging: Polycarbonate has established itself as the material of choice worldwide for the production of refillable 5-gallon water bottles (19 l). The large bottles are used to supply drinking water to the population in developing and threshold countries and in areas without an adequate public water supply. In North America, Europe and the major cities of Asia, they are used in combination with refrigeration devices. New on the market are housings for these polycarbonate water coolers. With a weight approx. 6 kg, the housing is actually the biggest extrusion-blown moulding to be made of polycarbonate.

The PC consumption for these water bottles is growing dynamically and amounted to approx. 70 000 t worldwide in 2001. By 2006, the volume for this segment is estimated to rise to approx. 100 000 t/a. Branched, high-viscosity polycarbonate grades developed specifically for this application comply with the relevant guidelines (FDA, NSF) for food-contact applications. The material is entirely transparent, making it easy to see how empty the bottle is. Above all, PC bottles are so hard, break-resistant and dimensionally stable that they can be filled more than 100 times. It is precisely this long-term serviceability that makes PC superior to other materials such as glass, PVC and PET. Because of the amorphous characteristics and high thermal resistance of PC, the bottles are also dimensionally stable at the high cleaning temperatures of between 60 and 80 °C, and they do not exhibit any post-crystallization. The five-gallon polycarbonate water bottles are nowadays produced mainly by extrusion blow moulding, but also by injection stretch blow moulding (Fig. 6).

Automotive: Car headlamp lenses of polycarbonate have now become established throughout the world. In 2001, approx. 50 000 t of PC was used for this application alone. The main advantages of PC compared with glass are its design scope and its much lower weight. For practical application, the surface of the lenses must be made scratchproof, chemical-resistant and UV-resistant. For this purpose, the industry has developed special scratch-resistant coating systems based on polysiloxane, polyacrylate and polyurethane. The combination of polycarbonate with the scratchproof finish had to

successfully withstand comprehensive testing before being chosen for this application (e.g. 3 years of outdoor weathering in Florida and Arizona as per SAE J576) and had to comply with certain standards (ECE, FMVSS) and demands on optical quality.

Bayer and Daimler Chrysler teamed up to develop an innovative rear flap module for the C class sports coupé. The UV-stabilised material is set to a transmission of 65 % and coated with a polysiloxane finish from GE Bayer Silicones.

Optics: In the optics segment, polycarbonate is increasingly becoming the preferred material for sunglasses, sports eyewear and protective goggles (Fig. 7), and also for corrective lenses. The material has high impact strength and is therefore particularly suitable for eyewear for children and sports enthusiasts. Under extreme climatic conditions, for example at sea or in the mountains, a built-in UV protection has proved to be particularly useful. Other advantages compared with glass and thermosetting plastics are its high refractive index with high light transmission and its ease of processing by injection moulding. In the United States, where liability plays a significant role in the event of eye injuries, around 30 % of all corrective lenses are now made of PC. In Europe, however, the proportion is still below 3 %. The scratchproof coating normally consists of a single layer and is heat-curing. Functional layers such as antireflex or antifog can also be applied to the coating. Finally, a hard plasma layer based on silicon is applied. A typical characteristic of PC eyewear is its high wear comfort.

Medical: The main applications for PC in the medical segment are dialysers, blood oxygenators (Fig. 8) and tubes and other elements for carrying blood and infusion solutions. The main reasons for choosing polycarbonate for these applications is its sterilisability in steam and hot air, its good compatibility with body fluids and its transparency, temperature resistance and toughness. Worldwide PC consumption in the medical segment in 2001 was approx. 60 000 t. Because PC has proved to be an ideal material in medical practice, demand is likely to increase further in future with ongoing development in the medical sector. New lipid-resistant and gamma ray-sterilizable polycarbonate grades extend the range of possible applications even further. The Injex injection system (manufacturer: Rösch AG Medizintechnik), introduced in 2001, has been very well received indeed. The liquid medicament is injected, virtually pain-free, into the tissue through the skin – but entirely without a needle. Instead, the technique is based on the very brief application of high pressure. The sterile ampoules have been previously filled with the medication, and the injection system is no larger than a ballpoint pen, is maintenance-free and does not need to be sterilized.

Application and Product Developments

The firm Exatec, a 50:50 joint venture between Bayer and GE Plastics, has been working intensively for several years on the further development of automotive glazing made of polycarbonate. The idea is to replace the glass in the side and rear windows with lightweight, break-resistant polycarbonate. One of the main challenges involves developing surface coatings for the polycarbonate that can satisfy the stringent specifications with regard to scratch resistance, weather stability and chemical resistance. Considerable success has been achieved with systems based on nanomer coatings (developed by Bayer AG and INM, Saarbruecken/Germany) and GE siloxane coatings. Apart from this, coating systems based on the plasma technology are under development.

One area of product development is focused on modifying the properties of polycarbonate through the specific incorporation of comonomers. As a result, the glass transition temperature of PC is raised through co-condensation with bisphenol TMC. Key applications here are to be found in the fields of automotive lighting and electrical engineering. For example, car reflectors and headlamp lenses are already being made of this material, which covers the heat distortion temperature range up to approx. 200 °C. Parts for hair dryers are also produced from the impact-resistant material, and in medical technology, polycarbonate is used for the manufacture of dental and surgical instruments that are sterilized in hot steam.

A further new development resulting from modification of the bisphenol structures is a polycarbonate marketed by Teijin Bayer Polytec Ltd., a 50:50 joint venture between Teijin Chemicals Ltd. and Bayer Ltd. Japan, for special applications in the field of optical storage media.

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Fig. 2. Breakdown of engineering thermoplastics 2001 (global)
Verbrauch Welt: 12 Mio.t (Wert: > 25 Mrd. EUR) = consumption world: 12 million t (value: > EUR 25 bn); Wachstum = Growth; ohne PC für Blends = without PC for blends

Fig. 3. Global consumption of PC including PC for blends from 1990 to 2001

Fig. 4. Regional distribution of global PC demand, including blends, in 2001
Europa = Europe; Japan = Japan; übriges Fernost = Rest of Far East; Rest der Welt = Rest of the world; Nordamerika = North America; Verbrauch Welt: 1900 kt (Wert: ca. 5,8 Mrd. EUR) = consumption world: 1900 kt (value: approx. EUR 5.8 bn); Wachstum = Growth

Fig. 5. Stacks of optical data carriers – CD production at Warner Music in Alsdorf/Germany

Fig. 6. Watercooler with 5-gallon water bottle of polycarbonate

Fig. 7. Good vision and optimum eye protection with protective goggles made of polycarbonate

Fig. 8. At the heart of a modern heart-lung machine is a blood oxygenator, which enriches the blood with oxygen and removes carbon dioxide