Looking Back. Over three million visitors have watched the Football World Cup live in South Africa. Most of them can scarcely have been aware that the modern architectural designs created for many of the stadia would have been virtually impossible to implement in practice without engineering plastics. Among such materials, the high-tech plastic polycarbonate (PC) is now used in numerous stadia for innovative roof and facade surfaces. But this is just one of many applications for PC. Discovered 57 years ago in Uerdingen, Germany, this extremely versatile material is now commonplace in the best sense of the word. Behind polycarbonate lies a material that has been writing its own success story for nearly six decades.

Polycarbonate – How a High-tech Material Conquered the World and Continues to Do So

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Even in his doctoral studies back in 1944, Dr. Hermann Schnell dedicated himself to the "Structure-property relationships in polyamides" – and engineering plastics were to play a central role in the further career of the researcher. In 1953, as head of Bayer's Main Science Laboratory in Uerdingen, he studied the reaction of phosgene with aromatic bisphenols. The polycondensates formed were also accessible through melt transesterification of bisphenols with diphenyl carbonate. This gave rise to a completely new class of thermoplastics with hitherto unknown properties, the aromatic polycarbonates. The enormous commercial potential of the polycarbonates was soon realized and industry, too, was enthusiastic after initial skepticism.

Translated from Kunststoffe 8/2010, pp. 20–26
Article as PDF-File at www.kunststoffe-international.com; Document Number: PE110415

Dr. Hermann Schnell, who discovered polycarbonate

Still in 1953, Bayer filed a patent application for the innovation – under the name Makrolon.

A Plastic Conquers the Market

In November 1958, the first polycarbonate production plant came on stream at Bayer's Uerdingen site. The monthly capacity was 40 t. In 1959, the plastic was presented to the trade public for the first time at the Plastics Exhibition in Düsseldorf, Germany. While PC was initially used for plastic films and covers for electrical switch and fuse boxes, by the 1960s it had become a household name, so to speak, in the form of plates and dishes. From 1971, the construction industry discovered PC for itself. Highly fracture-resistant and much lighter than glass, solid and multi-wall sheets made from Makrolon are used as glazing for greenhouses, conservatories, car ports and patio roofs. And even when elegant roof structures are required, architects are increasingly relying on the plastic from Uerdingen.

Blends: a Strong Combination

From 1977 onwards, it was realized that blends with other thermoplastics could

Roofing design for the BayArena football stadium: the roofing material is polycarbonate because of its transparency, stability, impact strength and weathering resistance (figures: Bayer MaterialScience)

open the door to new applications. The Bayer chemists had previously developed high-performance blends from PC and acrylonitrile-butadiene-styrene (ABS) for the first time. In the ensuing years, these were used in rapidly increasing amounts under the name Bayblend for applications such as flame-retardant housing materials for office equipment or super-tough dashboards and center consoles in automobiles. And another highly promising field of application made a powerful impact on an avid market: computers.

Revolutionary Disk

A new, epoch-making application for PC resounded on stereo systems in Europe for the first time in 1982. The audio compact disk (CD) technology developed by Philips, PolyGram and Bayer brought about a revolutionary change in the music industry. These optical data carriers produced from Makrolon not only made it possible to store music in unprecedentedly high quality but also permitted immense quantities of data to be stored in a minimal space – 24,000 typed DIN A4 pages can be stored on a standard 740 MB CD **(Fig. 1)**.

Fig. 1. CD stack: the polycarbonate audio compact disk brought about an epoch-making revolution in the music industry

Beverage and Automotive Industries Enjoy Success with PC

In the early 1990s, the bulky 5-gallon refillable water bottle made from PC made its breakthrough – thanks to the increasingly widespread use of water coolers. By 1992, European automotive manufacturers also became enthused with polycarbonate. Because it allowed much greater design freedom and considerable weight savings, Makrolon became the leading material for car headlight lenses, diffusers and covers. From 1999 onwards, the Bayer scientists intensified their work on automobile glazing itself – with excellent future prospects.

DVD and Blu-Ray Disks Offer Storage Paradise

As a further development of CDs, DVDs **(Fig. 2)** have been conquering the world market since 1996. There is space for a 135 min-long feature film on these 12 cm silver disks, which have a storage capaci- →

Fig. 2. HD-DVD: the high-definition successor to the DVD is also based on polycarbonate, works with a blue-violet laser that gives the product its name, and has a storage capacity of up to 50 GB

ty more than seven times larger (4.7 GB) than CDs. In 2006, the Blu-Ray disk finally emerged onto the market, bringing digital picture content of a much higher quality. This high-definition successor to the DVD is also based on Makrolon, works with a blue-violet laser that gives the product its name, and has a storage capacity of up to 50 GB. The enormous quantum leaps in storage capacity from the CD to the Blu-Ray have been achieved with ever smaller pits, narrower track pitch, shorter wavelengths and a smaller reading/writing laser beam diameter. These technological advances are only possible because even nanoscale structures can be molded into PC surfaces with very high precision.

Current Applications and Future Visions

The market is huge and the potential applications more varied than ever. Besides the established applications for PC, Bayer MaterialScience is constantly researching new ways to make products more (energy-)efficient, safe or economic with PC. So polycarbonate is helping to support the sustainable philosophy of the company and actively address the many different trends and drivers in its customer industries.

Optical Data Carriers (ODS): So far, these are the most important application for PC with a share of around 25 % of the total market. The current trend is slightly down (about -5 % p.a.) – coming from a high level. But in the case of individual products, the signs point to continued growth. For example, the Blu-Ray formats are currently booming. At present, consumption of PC for these formats is doubling virtually every year. It is clear that the storage requirement of the global population is growing exponentially and therefore optical storage media will continue to be an important mainstay of the PC market in the coming years.

Water Bottle: In 2008, some 100,000 t PC were processed for 5-gallon bottles. These bottles produced from Makrolon WB1239 can be refilled up to 100 times – an important advantage over glass, PVC and PET. Multi-trip milk and yogurt bottles made from PC are also gaining popularity in Europe at the expense of disposable packaging and multi-trip glass bottles. Plastic packaging is becoming increasingly lightweight and durable, so reducing not only the use of the raw materials required but also transport weight and the corresponding transport costs. Overall, therefore, the ecobalance for plastic packaging, i.e. the total energy consumption for manufacture, transport and disposal, is more efficient than for other types of packaging.

Medical Technology: Even in highly challenging, strictly regulated application sectors such as medical technology, the use of PC is growing in importance. Polycarbonate is robust, available in transparent and opaque grades and readily sterilizable. In medical technology, it is used mainly for dialyzer housings. Intravenous access systems, dispensers for self-medication and connectors and couplers for medical devices could also be produced from PC (in future).

Electrical/Electronics: PC+ABS blends, in particular, are used today in data and information technology as well as in electrical engineering and electronics. Safety and ecological advantages are important drivers for this. European standard EN 60065, which came into force on July 1, 2010, will increase PC business for LCD television sets **(Fig. 3)** according to expert forecasts. The standard specifies that manufacturers must protect their TV sets with an efficient flame-retardant system. This means that ABS, PMMA+ABS or polystyrene can no longer be used in television sets without flame retardants. Flame-retardant PC grades such as Makrolon FR or Bayblend FR, on the other hand, are permitted. The new EU WEEE and RohS directives also favor the use of halogen-free flame-retardant thermoplastics. To avoid higher disposal costs, halogenated HIPS and ABS materials are increasingly being re-

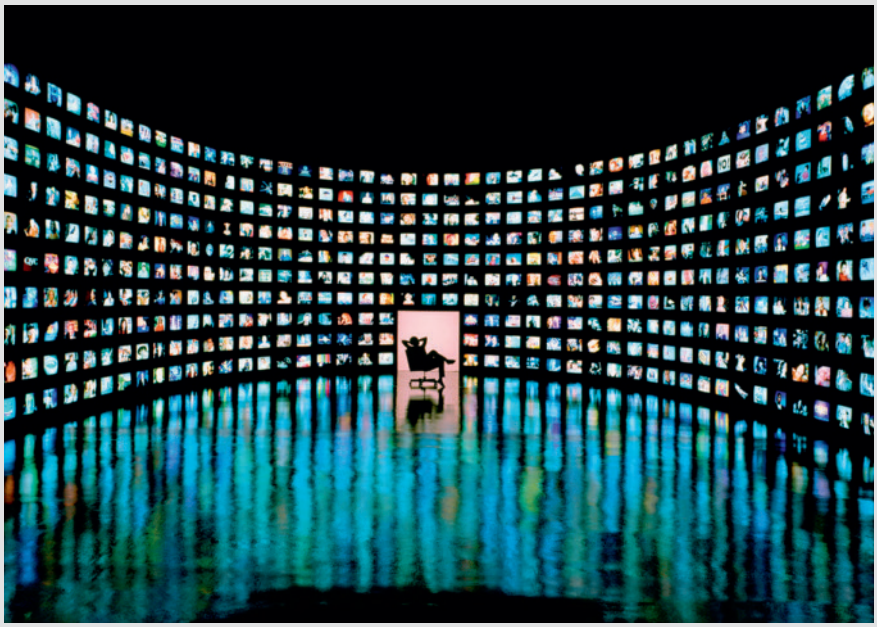

Fig. 3. LCD television sets: PC business for LCD television sets will continue to increase according to expert forecasts

Fig. 4. Smart roof: the latest Smart car has a panoramic roof made from polycarbonate

Fig. 5. RXI collimator lens: the optical properties of polycarbonate make it a material of choice for the production of lens optics

placed by halogen-free, flame-retardant PC blend grades. Stricter test criteria for ecolabels such as the "Blauer Engel" are also reinforcing this trend, while increasing requirements for the protection of appliance electronics in many household applications are continually leading to new developments in the blend sector. Hydrolysis-stabilized grades such as Bayblend FR 3008 HR (Hydrolysis Resistant) are entering the market. This special flame-retardant (PC+ABS) blend is highly resistant to extreme hot, moist environments and offers an excellent performance profile in terms of chemical resistance, moisture absorption and visual appearance, e. g. color stability.

Automobiles: Almost all car headlamps worldwide contain PC and the material is firmly established as "state of the art". (PC+ABS) blends are also finding increasing application for interior and exterior components. The Bayer researchers see a clear future market in auto glazing. Thanks to its freedom of design, fracture resistance and light weight, PC will achieve considerable growth in this sector over the long term – particularly for large panoramic roofs or mobile modular parts **(Fig. 4)**. A good example is the current Smart Fortwo, which boasts the world's largest PC-based panoramic roof in a serial production vehicle (1.2 m^2). The transparent component is produced from Makrolon AG 2677, a polycarbonate specially developed for auto glazing, while Bayblend T95 MN is typically used for the frame component. Despite its size, the roof module can be produced warpage-free with only very small internal stresses and excellent surface quality by 2-component injection-compression molding. The roof element is over 40 % lighter than comparable glass solutions and so considerably improves the fuel efficiency of the vehicle. Back injection molding of preformed, printed plastic films (film insert molding) also opens up enormous design options. It enables additional functions such as screen heating, aerials and IR reflection technology to be integrated into roof modules or rear screens directly during production. Component surfaces can also be specially tailored and decorated in the same mold using the latest direct skinning or direct coating processes. For this purpose, they can be coated with polyurethane foams or resins. Innovative PC films with intelligent functionalities are increasingly being used in auto interiors. A good example is the PC film Makrofol TP244, which – thanks to its thin, co-extruded UV protective layer – offers high light stability and UV resistance and therefore excellent resistance to yellowing.

Construction Elements and Architectural Glazing: Plastic sheeting for the construction industry accounted for some 15 % of global PC consumption in 2009. For solid and multi-wall sheets, special coextruded UV protective layers have been developed, which ensure effective protection against weathering in outdoor applications. As a result of its advantageous properties, the high-tech plastic is increasingly proving itself to be an ideal and very economic replacement for glass in the architectural glazing sector. The possibilities opened up here by solid and multi-wall sheets made from Makrolon are impressive in many respects. Highly stable and yet very flexible, the sheets can →

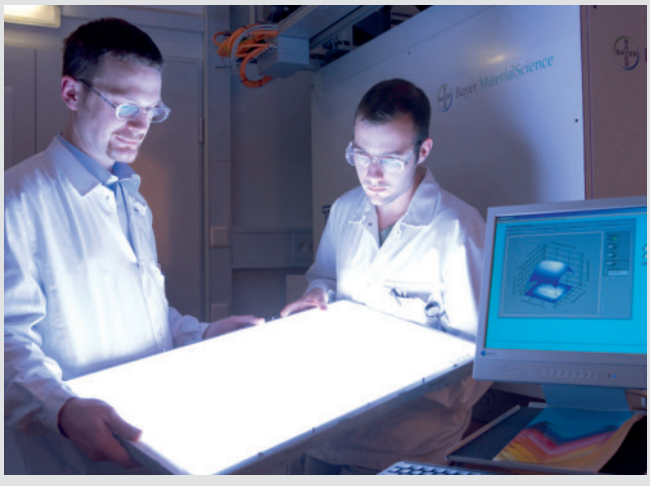

Fig. 6. Diffuser plates: a specially developed polycarbonate is used to produce diffuser plates for large LCD flat screens

withstand high wind loads and absorb wind movements without requiring solid sub-structures. They have high impact strength and can withstand extreme hailstorms, large snow loads and heavy rain. At the same time, they are light in weight (only a few kilograms per square meter) and easy to handle. Their high light transmission guarantees optimum light conditions without shadows or excessive light-dark contrasts. They also take care of safety by complying with important international fire protection regulations **(Title picture)**.

LED Applications: For some time now, the favorable properties of PC have made it a material of choice for the production of lens optics **(Fig. 5)** and optical fibers for energy-saving LED technology. These components have to meet very high requirements for light transmission, thermal stability and color consistency. Bayer MaterialScience now offers different polycarbonate grades **(Fig. 6)** for the LED market. Depending on lighting requirements, these can offer very high light transmission, good heat resistance or special stability under LED luminous flux or to UV radiation. The use of plastics in LED lighting concepts helps to achieve both uniform light distribution and superior light transmission for exceptional optical brightness at low energy cost **(Fig. 7)**.

Fig. 7. LED lenses: lighting concepts with LEDs offer exceptional optical brightness at lower energy costs

Furniture and Consumer Products: Highly design-oriented industries such as the furniture industry, the sports and leisure sector and the toy industry are relying increasingly on PC – especially for attractive, economic component solutions. For the chair industry, for example, Bayer MaterialScience has customized two highly transparent, extremely impact-resistant Makrolon grades and the very easyflowing (PC+ABS) blend Bayblend T65 XF, which give designers wide freedom of design compared with conventional materials because of their good melt flowability. Visual and tactile surface effects in line with the latest trends can be obtained by various plastics coloration technologies and new developments based on soft thermoplastic polyurethanes and hard thermoplastics such as polycarbonate and its blends. It is possible, for example, to produce warm, soft-touch surfaces that have excellent mechanical properties and very high abrasion and wear resistance. Such surfaces provide high serviceability and a long lifespan on a wide variety of furniture components, such as chair arms, seat elements, setdown surfaces, handles and knobs. Depth effects can be achieved by two-component molding, while for electroplated surface effects, special PC blends such as Bayblend T45 PG (Plating Grade) are available for many different applications. High-tech films with intelligent functionality are also very much in vogue. For example, PC films can be supplied that are electrically conductive, emit light when an electric current is passed through them, have a chrome-effect surface (electroluminescence) or are surface-modified to provide a soft-touch surface.

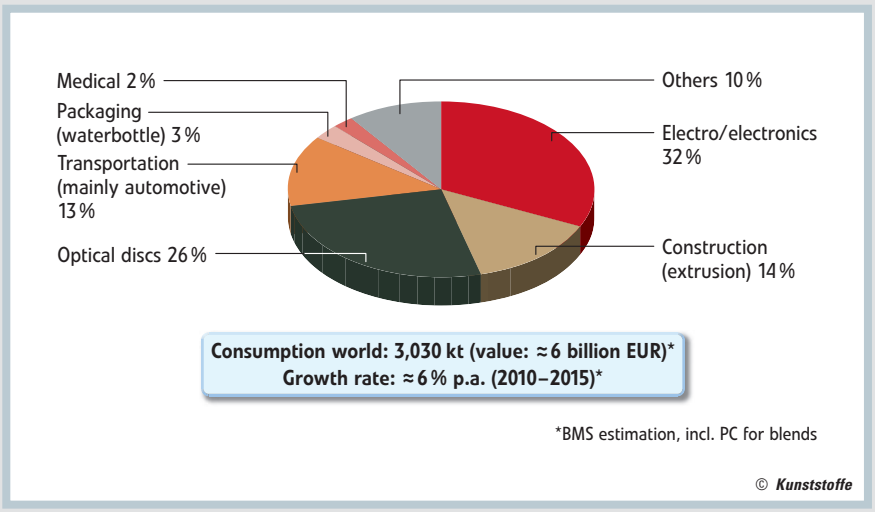

Fig. 8. World market for polycarbonate by application (2009)

Traffic Management Systems: The use of PC and PC blends in traffic management systems is no longer a future vision but everyday reality. Instead of glass, metal or PMMA, polycarbonates are increasingly finding application in housings and optics for traffic lights and rail signal lights, in lighting elements for construction site safety and lane markings, and also for parking meter housings. Their advantages over PMMA, which is also transparent, include dimensional stability, considerably higher impact strength, even at sub-zero temperatures, and resistance to vandalism.

A High-tech Plastic with a Future

Even over 57 years after its discovery, PC is a more contemporary material than ever and there appears to be no limit to its potential applications, holding out the promise of many more innovations to come. This is a "young" material perfected by experience – with a clear horizon ahead. No wonder, then, that the forecasts up to 2010 predict annual worldwide growth of around 6 % **(Fig. 8)**. ■

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