1 Introduction

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1.1 Historic Development

The car painting industry has undergone incredible changes by way of materials and processes development following the general progress of manufacturing technology from the start of the twentieth century until today. Early coating processes, that is, during the first half of the twentieth century, involved the use of air drying paints, sanding of each layer and polishing, all of which needed weeks for completion. All the coating steps were executed manually (Figure 1.1).

Different driving forces behind the development of better and more efficient processes have brought in dramatic changes over the last 100 years. Introduction of mass production requiring faster curing paints, better film performance in terms of corrosion and durability of colors, improved environmental compatibility, and fully automated processes for better reliability characterize the most important milestones in this field (Table 1.1).

The status of mass production of cars during the 1940s required new coatings providing faster drying and curing: the result – the birth of enamels! At the same time, owing to their limited availability, the natural raw materials used in the manufacture of the paints had to give way to synthetic chemicals. Crosslinking of paints became state of the art. The coating process could be reduced to a day including all necessary preparation time for the car body like cleaning, sanding, repairing, and so on.

The number of applied coatings had been reduced to four or five layers, all hand sprayed this time (Figure 1.2). The function of these layers were corrosion protection for the primers, smoothness and chip resistance for the primer surfacers (which are often applied at the front ends and exposed areas in two layers), and color and weather resistance for the final top-coat layer. In the 1950s the process of applying the primer changed to dip coating, a more automated process, but a hazardous one owing to the solvent emission of the solvent-borne paints. Explosions and fire hazards then forced automotive manufacturers to introduce either waterborne paints or electrodeposition paints. The latter, which were introduced during the

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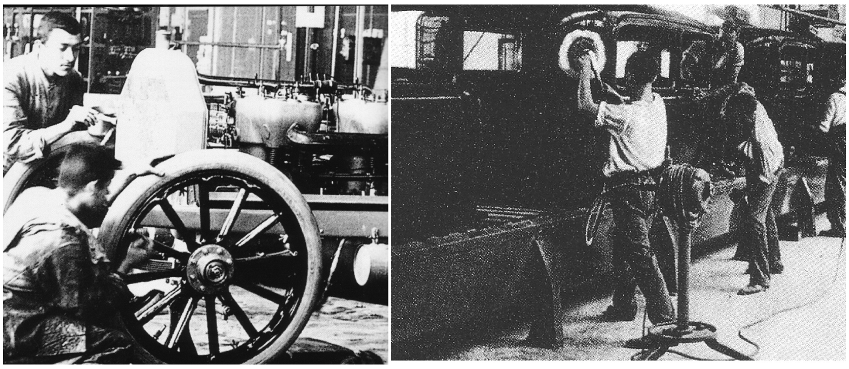

Fig. 1.1 Painting of cars in the 1920s and 1930s.

Table 1.1 Milestones and driving forces in the car coating process

Year	Topics/Driving forces	Aspects
1920	Manual painting	Time-consuming process : weeks
1940	Mass production	Enamels/oven/time : day
1970	Improved film performance	CED/2-layer top coat/new materials
1980	Environmental compliance	Waterborne coatings/powder/transfer efficiency
2000	Automated processes	First time capability/time : hours

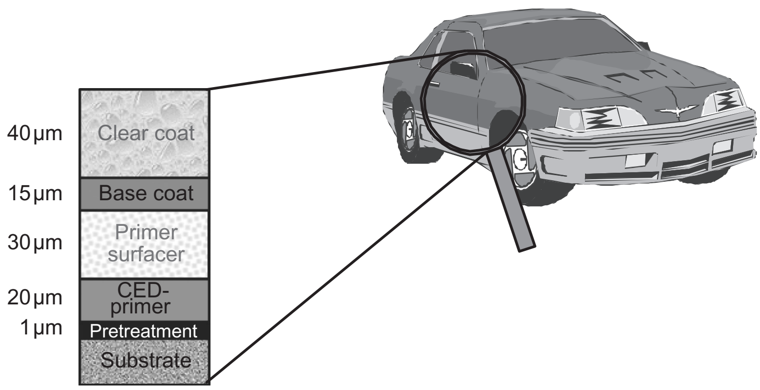

Fig. 1.2 Scheme of the multilayer coating of cars.

late 1960s, are more efficient in terms of material transfer as well as throwing power that is necessary for improved corrosion protection of the inner parts of the car body.

In the 1970s the anodic deposition coatings, mostly based on maleinized polybutadiene resins, quickly gave way to cathodic ones owing to better corrosion protection by their modified epoxy resin backbones and reactive polyurethane-based crosslinkers, increased throwing power, and higher process reliability. At the same time, the single layer top coats were gradually replaced by two-layer top coats consisting of a thin base coat and a thicker clear coat applied wet-on-wet. The base coats are responsible for color and special effects (for example, metallic finish), whereas the clear coats provide improved durability using specially designed resins and formula ingredients like UV-absorber and radical scavengers. Today, most clear coats in Europe are based on two-component (2K-) formulation consisting of an acrylic resin with OH-functions and a reactive polyurethane crosslinker. The rest of the world still prefers the one-component technology based on acrylic resins and melamine crosslinkers. An interesting one-component technology based on carbamate functionality has been recently introduced in the United States [1].

All these developments contributed to an improved film performance resulting in better corrosion protection and longer top-coat durability – for example, gloss retention for up to 5–7 years was observed in Florida.

Furthermore, raw material development in the pigment section, with improved flake pigments based on aluminum and new interference pigments that change color depending on the angle in which they are viewed, has resulted in enhanced brilliance and color effects of automotive coatings [2].

Along with this development of coating and paint technology, spray application techniques also underwent significant improvements. Starting with simple pneumatic guns and pressure pots for paint supply, today, craftsmanship in painting is no longer needed. Several factors have contributed to the development of coating machines and robots and the state of automation that is present today. The first factor was the health risk to the painters who were exposed to solvent emission from paints in the spray booth and the investment in safety equipment, which was often unsuitable for them. The second factor was the hazards of the electrostatic application technique. Yet another factor was the lack of uniform quality in a manual painting job.

Because of the latest developments in wet-on-wet coating technology, coating machines, automated cleaning processes, and modern paints, the time taken today for the coating process, including pretreatment, can be as short as 8 hours for a car body leaving the body shop and entering the assembly line (Figure 1.3) [3].

Together with the continuous improvements of the application technology, new water-based materials were developed to contribute toward the legally enforced environmental compliance of the processes. The first water-based base coats were introduced at Opel in Germany in the 1980s, followed by water-based primer surfacers in the 1990s.

Investments in modern paint shops vary from €200 up to €600 million for coating 1000 units a day. Today, painting technology for the car industry has been more

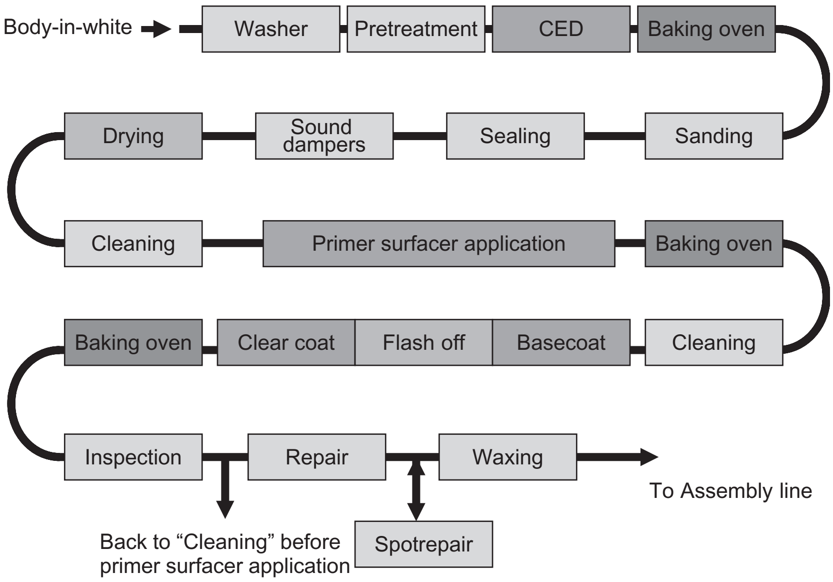

Fig. 1.3 Process steps in modern automotive paint shops.

or less standardized all over the world. Inorganic pretreatment, cathodic electrodeposition, liquid or powder primer surfacer, liquid base coats, and one-component or two-component solvent-borne clear coats are mostly used today. This is a result of the consolidation of the engineering and coating line manufacturers and paint producers into just a handful of major players. In 2002, 70% of the car coating market was in the hands of Dupont, PPG, and BASF.

As of today, the technology of powder coatings has reached a point where many car manufacturers have decided to introduce environmentally compliant technology more aggressively. Today, powder is established as the primer surfacer in North America: at Chrylser in all actual running plants, at GM for their truck plants, and in all new paint shops. In Europe, in a number of plants at BMW, powder is also used as a clear coat. [4].

Over the same period of time, body construction materials have also changed significantly. Starting with pure steel bodies, today the share of aluminum and magnesium, as well as plastic, as raw materials for specific car components or hang-on parts can account for about 30% of the weight of the car. On an average, half of this is plastic. The main focus is on weight reduction, design variability, and cost (Figure 1.4).

Starting with bumpers in the 1970s, and moving on to fenders and hoods, many of the exterior parts are now made of specially designed plastics. The coating process is predominantly outsourced for these parts, even though some car manufacturers assemble the parts in the coating line and apply the original base coat–clear coat technology on these parts to overcome color match problems.

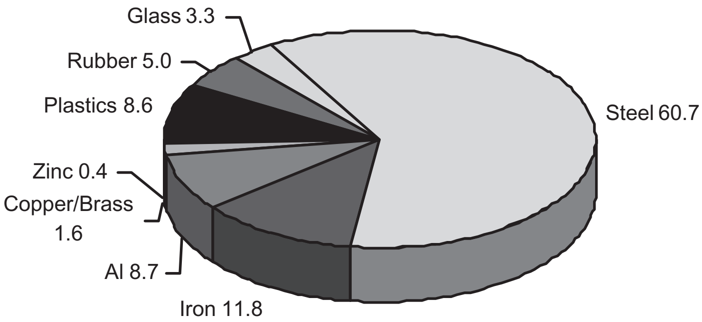

Fig. 1.4 Share (%) of different material classes for car manufacturing (source : Ward's Communications, Facts & Figures 2002).

Interior parts made of plastic materials were introduced in the 1960s and are today increasingly being coated by specially formulated paints for providing the 'soft feel' touch that gives the plastic an improved acceptance by the customers. These parts were mostly painted by the part manufacturers and supplied to the automotive industry as complete modules to the assembly line. Special laser coatings have been developed to inscribe symbols of functions on coated dash board or other units in the interior of a car.

Another increasing application of coatings is connected with the modern design of head lamps made of blow molding compounds(BMC) for the head lamp reflectors covered by a polycarbonate lens. Both parts are coated dominantly by UV coatings.

Many other exterior parts like hoods and trunk lids, as well as other body segments, are increasingly made of aluminum or sheet molding compounds (SMC). In addition to the aspect of careful construction in respect of building galvanic elements, pretreatment chemicals and the process of multimetal bodies had to be developed. This was a demanding task that needed avoidance of any harmful heavy metal ions like chromic-VI. The complete aluminum body still remains a niche product.

Connected with an increased share of multicomponent parts of different substrates, the welding process for manufacturing cars has been partially replaced by other assembling techniques like clinching and riveting. Glewing, a technology known from the air transportation industry, has become very important. This technique is based on surface treatment and product application similar to coatings. On the basis of the use of interface with coating layers like gluing back-windows on electrocoat layers and its increasing application, this will be described in Chapter 10.

The performance requirements for an OEM (Original Equipment Manufacturer) coating of passenger cars are many and diverse. They can be attributed to corrosion protection, durability, including stone chip resistance, and appearance. One should bear in mind the extent of extreme stress that cars are exposed to throughout their life span. High temperatures up to 70 °C on dark colors in Florida and similar regions, as well as low temperatures of −50 °C in polar regions, permanent temperature fluctuation of 10–20°C daily, stone chip attacks on unpaved roads, high loads of salt in coastal regions, as well as in wintertime, high ultraviolet radiation in combination with dry and humid periods, the action of acid or alkaline air pollutants from many sources, and the physical and mechanical stress in vehicle washing installations are the most important among the many factors. Recently, the gloss, appearance, and effect coatings became important factors for selling cars by underlining the image and personality of the car and its driver.

Because of the fact that many resources have been directed to the environmental improvement of paint application as well as toxic aspects of the paint formulas, the performance of automotive coatings has increased significantly. Even the film thickness of a car coating today is only 100–140 μm, which needs, in most coating processes, about 9–16 Kg deposited paint per car; the corrosion protection and the long time durability of color and gloss is about two times higher than what it was 25 years ago. Three main factors have contributed to this: new substrates, introduction of cathodic electrodeposition paints, and the two-layer top-coat system with a special designed clear coat for long term durability. The life time of a car is no longer related to the corrosion or durability of the coating and color.

The color of cars has become a very important design tool, significantly supporting the purchasing habits of customers. For this reason, color trends are being observed by the paint and automotive industry together to develop trendy colors for the right cars.

The color variability has been increased at the same time. Today's customers, especially in the premium car level, can demand whichever colors they want at a cost. New color effects like 'color flop', which is a coating providing different color impressions to the customer depending on the angle of vision, have entered the scene [5].

The latest significant milestone in the history of the development of car painting is the combination of highly efficient application techniques like high rotational mini- or micro-bells and the painting robots (Figure 1.5). This has lead to the highest degree of transfer efficiency and reliability, resulting in an efficiency of 90% and more of defect free coatings in modern paint shops [6].

The application of sealants, sound deadeners and underbody protection is very often a part of the coating process. These materials need to be dried. In an efficiency move, the primer baking ovens are mostly used for this process.

Shorter cycle time of car models requires faster planning and realization periods for designing new paint shops. Additionally, globally competitive business has brought into the focus of car manufacturers not only the respective investment costs, but also the running cost of a coating line [7].

At the end of the paint line, the application of transport coatings, wrap up of coated cars for company design on a commercial fleet, as well as safety measures, all become part of the coating processes connected with the manufacture of cars [8].

Quality assurance has reached a new dimension for automotive OEM paints and coatings. While time-consuming batch-to-batch approvals of the customer's specifications has been the order of the day, supporting-system approaches, for example, audit-management systems according to DIN-ISO 9001 and 14001, ISO/TS 16949, QS 9000 or VDA 6.1, have become mandatory for the paint industry

Fig. 1.5 Paint robot with electrostatic bell (source: BASF Coatings).

to be approved as a supplier to the automotive industry. So, right from the beginning, the development of new products has to be quality oriented to 'zero defect' levels through all the steps leading up to the delivery status.

At the same time, the testing and physical methods of describing the performance of paint and coatings have become much more precise and value based not only for the performance of the films, but also the performance during the application and film forming processes. In top-coat color specifications and in general physical color matching, especially, colorimetric data will replace visual inspections, which have reliability problems. The so-called 'finger print' methods have been developed to improve the performance of paints during the application processes [9]. Film performances like durability and corrosion protection, and mechanical performance like scratch, mar, and gravel resistance are very predictable in short term testing procedures today.

1.2 Legislation

Another driving force for finding new coating formulas is the passing of legislative acts all over the world calling for a ban on toxic components in all the formulae to the maximum possible extent [10]. So lead- and chrome-free paint formulas are today 'state of the art'. Also, the emission of volatile organic compounds (VOC) has been restricted, especially in Europe and the NAFTA (North American Free Trade Agreement) region for the last 20 years, to numbers that are defined in various ways and controlled in NAFTA and Europe, and are about five to ten times lower than what they were 30 years ago. This was reached by simultaneous material and process development as described herein. The industry has to deal with moving targets set by the authorities according to the best available technology. In general, the emission of any type of 'greenhouse gases' is in worldwide focus based on the 'Kyoto' protocol. Life cycle assessments are gaining awareness [11].

Owing to the fact that the most important application processes of automotive paints release solvents and that the composition of coatings can have more than 15 ingredients, together with the global agreements on environmental targets, the political scenario in North America and Europe was to focus first on paint consumers and manufacturers for improved environmentally compatible products and application processes.

The response in the 1980s in North America was to increase the solid contents and decrease the solvents of the actual solvent-borne paint formulations. New resins had to be developed and formulation as well as application conditions had to be optimized in the direction of sagging resistance and surface and film properties. The relative increase of solids by about 20% generated a completely new technology. The legislation controlled the progress by measuring the solvent input in the factories.

In Europe the resources for research and development were directed to waterborne coatings first, resulting in the introduction of waterborne base coats. Solvent-borne base coats were the paints providing the highest amount of solvent emission owing to the very low solid content of 12–18% at that time. Later in the 1990s waterborne primer surfacer and some waterborne clear coats were introduced. The legislation in Germany supported abatement technology to meet its requirements. The new European approach of the VOC directive of 1999 now combines after-treatment with the pragmatic approach of North America, mostly the United States.

Both paint development directions resulted in rather different paint formulations, creating problems for the South East Asia (SEA) region, which still has to decide which way to go. Signals and recent decisions of Toyota, Honda, Nissan, and Mitsubishi favor the waterborne products.

Safety standards for the handling of paints in the paint kitchen as well as application booths are quite uniform around the world. The personal safety equipment in spray booths now mostly consists of complete overall, mask, and respiratory systems protecting the worker from any contamination. A greater use of robots keeps workers out of the paint booth. They become engineers who program and run the robots and look into other booth parameters.

Harmful chemicals and additives have been tested comprehensively during the last 30 years. Many products have been abandoned either by the car manufacturers themselves or by legislation. Among these are lead, in electrocoatings and pigments, chromium, in primers and electrocoatings, cadmium, in pigments, many solvents qualified as HAPS (Hazardous Air Polluting Substances), and monomers like acrylonitrile, acrylamide, and so on, which belong to the cmr (carcinogenic, mutagenic, reproduction toxic) products. Special awareness has been created with respect to the biozides in Europe [12]. Other VOCs may contribute to the generation of ozone in the lower atmosphere and so they have been limited by legislation, step by step, leading up to the best state-of-the-art technology of the paint application process [13] as well as paint product development. Significant steps have been made in this respect by the introduction of waterborne base coats, waterborne primer, and the slurry-clear coat. Further reduction in VOC can be achieved by powder primer surface and powder clear coat [14].

In recent years, legislation in Europe focuses on the harmful and environmentally significant impact of chemicals. This will also lead to further replacement of ingredients and components in paint formulation [15].

1.3 Automotive and Automotive Paint Market

In 2004, car manufacturers, worldwide, produced about 58 million cars and light trucks (vans, mini-vans, pickups). Europe, North America, and Japan are traditionally the largest producing regions, accounting for about 78% of all cars (Figure 1.6).

SEA including Korea, China, and India, is gaining importance as a consumer market as well as a producing region. This is a change from the past and will change in the future owing to two main reasons:

1. Today's quality concepts in manufacturing as well as painting cars allow car manufacturers to produce wherever workforce is available. This drives most of them to regions with low labor costs.
2. Most car manufacturers produce world class cars, which can be exported and brought into all market places around the world.

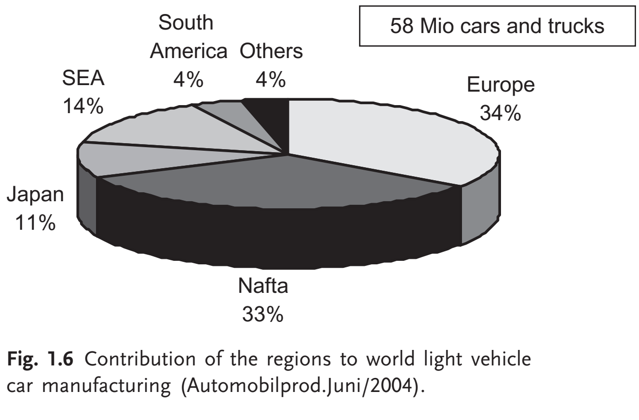

Fig. 1.6 Contribution of the regions to world light vehicle car manufacturing (Automobilprod.Juni/2004).

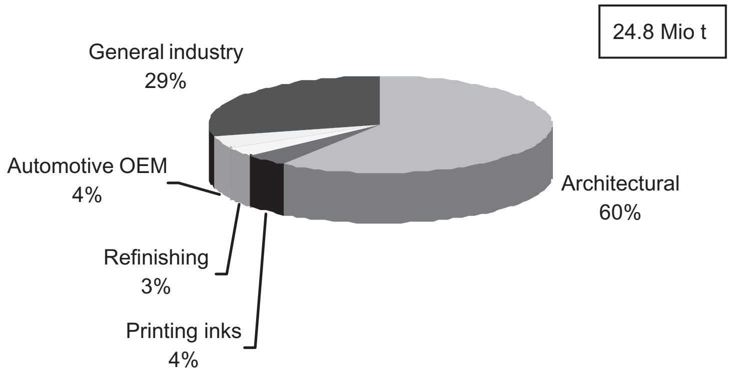

Fig. 1.7 Volume of the worldwide paint market as of 2002.

Among the limiting factors are the supply bases of components and hang-on parts, especially when it comes to just-in-time deliveries. This leads to certain regions where the car manufacturers would prefer to settle in the future like North Carolina, South Korea, Eastern Europe, and Shanghai, for example.

Since the 1980s, the outsourcing of manufacturing components and integrated modules like headlamps, fenders, bumpers, doors, and roof elements for direct delivery to the assembly line represents the global trend in worldwide car manufacturing so that the 'value added' is transferred to the automotive supplier industry. Since 2000, the supplier industry, which has a 40% share of the worldwide production value in the car industry and which includes more of design work, is increasingly focusing on innovation efforts and is consolidating to become a global industry.

The worldwide market volume of car paints of about 1.0 Mio t consists of electrodeposition coatings, primer surfacers, base coats, and clear coats, as well as speciality coatings consumed in the automotive coating lines and in the supplier industry, only counts for about 4% of the total paint market (see Figure 1.7). The biggest share contributes to the architectural market, followed by general industry (OEM market), which, in other statistics, like in North America, includes the contribution of car paints. From a technological standpoint, car paints as well as their coating processes are valued as the most advanced technologies both by coating performance, and the efficiency and reliability of the coating process. These high standards and requirements forced many players out of business, resulting in the fact that today just three main paint suppliers dominate the worldwide automotive OEM paint market. Regional paint manufacturers exist mostly in Japan and SEA.

In recent years, the method of conducting business activities has begun to change significantly. With the 'single sourcing' concept in which one paint supplier delivers all products and takes responsibility for all paint-related problems of the coating process, the business arrangements between paint manufacturers and the automotive industry has reached a point where the responsibility of running paint lines as well as cost targets have been taken over by the paint supplier [16]. The so-called *Tier 1*' suppliers manage the various degrees and levels of cooperation with

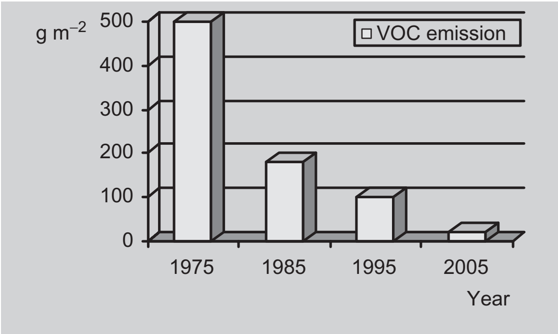

Fig. 1.8 Reduction potential of volatile organic compound (VOC) emission of the automotive coating process in gram per square meter body surface based on paint and process development (best available technology).

the customer. *Tier 2* suppliers manage the total paint shops including engineering, logistics, auxiliaries, quality control, and staffing [17].

Targeting the cost per unit and not cost per paint, together with new processes [18], modern application techniques, and paint formulations has brought the efficiency and environmental compliance of the coating processes in terms of VOC to a level that could not have been imagined 30 years ago (Figure 1.8). This has happened with an increased performance level of coatings in terms of corrosion protection, the top coat's long-term durability in respect to chip resistance, and color and gloss retention.

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