JOINING OF PLASTICS BY ADHESIVE BONDING IN AUTOMOTIVE ENGINEERING

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ABSTRACT

The use of composites in automotive engineering has increased and is expected to further increase in the future not only because of the weight saving opportunities but also for other reasons like design freedom. Using composites requires in many cases the joining of components to form the ready part. Of course adhesive bonding has gained an important position.

In order to fulfill the high requirements of the automotive industry in regard of strength, durability, crash performance, costs and the like all steps from development to production (composite selection, joint design, bonding process) require special attention. The purpose of this paper is to provide some fundamental information about bonding followed by the presentation of examples from the industry illustrating the benefits of bonding.

INTRODUCTION

The use of plastics in automotive engineering has increased over the past years and is expected to increase further on. Besides the traditional interior applications plastics are nowadays also used for exterior applications. This will not remain limited to bumpers, spoilers, trunk lids and lift gates but plastics will enter new applications like roof modules and front hoods (Fig. 1). Except for some rare exemptions thermoset materials like SMC and BMC have been used but the use of thermoplastics will increase.

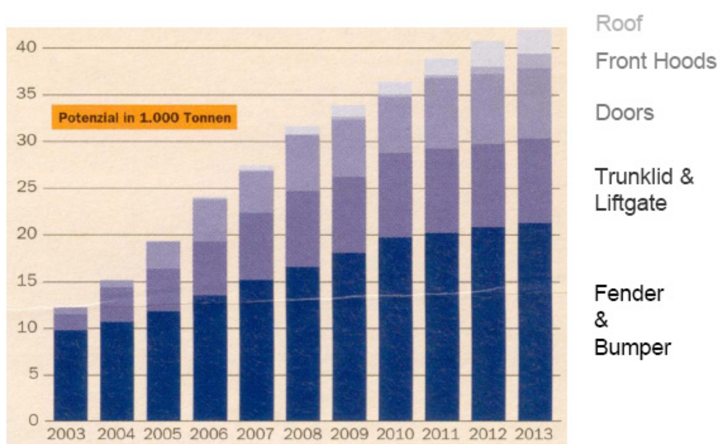


Fig. 1:
Estimated volume for exterior plastic automotive parts [1]

The reason for the increased portion of plastics in the material mix of a modern automobile is for sure not limited to the low density and the weight saving potential resulting in improved fuel consumption. Another important benefit besides its resistance against corrosion is related to the styling freedom. Shapes not possible to make from metal can be realized from plastics. In addition plastics offer cost benefits for low volume applications as well as for individualized parts for high volume models like the liftgate of the minivan family of Peugeot, Citroen, Lancia and Fiat.

Although there are significant benefits involved in the use of plastics there are also some disadvantages involved which are e.g.

- Class A surface, paint ability, colour matching, scratch resistance
- Resistance against chemicals
- Crash performance especially at low temperature
- Long cycle time in production
- Recycling issues (especially thermoset plastics)

The identification and selection of a suitable joining technology for plastic materials is of special importance. Besides mechanical joining technologies like snap fits, rivets, bolts and the like bonding as well as welding (limited to thermoplastics) is of high importance.

The wide range of different plastics with different properties does not only make plastics very interesting for all kinds of automotive parts but also requires special attention on selecting an adhesive system. The adhesive as well as the bonding process, e.g. surface pretreatment needs to be adjusted to special requirements of the materials to be bonded and also of course to the required performance of the bonded part.

WHAT IS BONDING - ADHESION AND COHESION [2], [3]

Bonding is defined as joining of two substrates using an adhesive. According to EN 923 an adhesive is defined as a non-metal binder that acts via adhesion and cohesion. Adhesion is the adhering of similar or different types of materials to each other and cohesion is the internal strength of a material, e.g. the adhesive. Looking at its cross section a bond (fig.2) consists of different layers:

- In the **adhesion zone** the adhesive has a modified molecular structure due to the effect of the substrate surface and the molecular interactions between adhesive and substrate. Depending on the adhesive and the substrate the interactions are of different nature and strength. The adhesive forces do have in common that they have a short range of about 0.1 to 0.5 nm.
- In the **transition zone** the chemical, mechanical and optical properties of the adhesive alters. The thickness of this zone can vary from a few nanometers up to the millimeter range and depends on the adhesive, its cure conditions as well as on the substrate.
- In the **cohesion zone** the adhesive possesses its nominal properties.

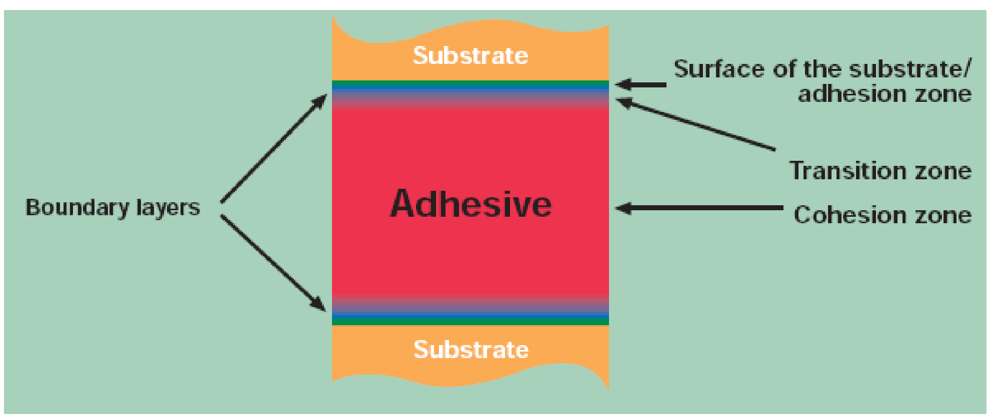


Fig. 2:
Cross Section of a Bond [2]

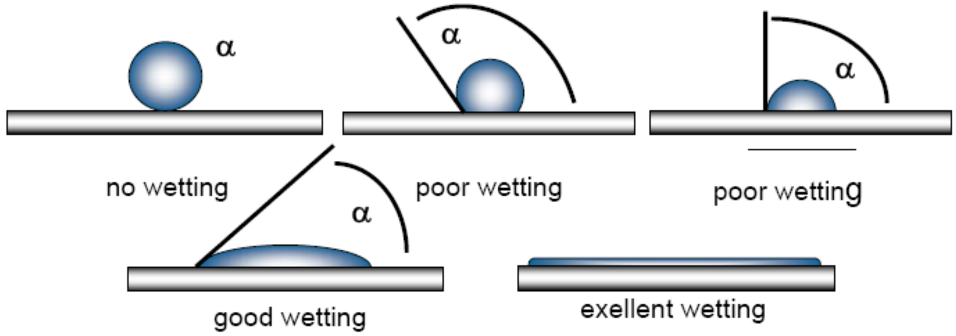
With this it becomes obvious that all three layers play an important role for the performance of a bonded structure. The strength of a bond is of course determined by the internal strength (cohesion) of the adhesive but also by the strength of the molecular interactions between adhesive and substrate in the adhesion and interaction zone. The long term stability depends directly on the resistance of the adhesion and cohesion forces to environmental parameters like humidity.

SURFACE PREPARATION [3], [4], [5], [6]

A prerequisite for forming an adhesive boundary layer (= adhesion- and transition zone) is a good wetting of the substrate by the liquid adhesive. The degree of wetting, which amongst others is determined by the surface tension of the substrate and the adhesive, is a criterion for the quality of the adhesion. With adhesive forces just having a rather short range it is obvious that the determining factor for the actual adhesion is the accessibility of a number of physically and chemically active structures on the substrates surface and in the adhesive.

The contact angle can be used as a measure for surface tension, the larger the contact angle the better a surface will be wetted by a liquid, e.g. an adhesive (fig 3).

Fig. 3:
Contact Angle indicating degree of wetting



It needs to be mentioned at this point that a good wettability of the adhesive is necessary for adhesion but is alone not sufficient. The formation of intermolecular interactions between substrate and adhesive is required as well.

The requirements which have to be met by a substrate to form a good and reliable bond can be summarized as follows:

- The substrate surface must have good wetting properties, namely the selected adhesive must distribute itself (spread) across the surface.
- The substrate must have good bonding properties; there must be the ability of forming intermolecular and chemical interactions with the adhesive
- The surface layer of the substrate must be securely attached to the substrate
- After bonding the surface must not change in an uncontrolled way

In many cases the surface of the parts to be bonded does not fulfill these requirements and then subjecting the substrate to a surface treatment needs to be considered. In general a surface pretreatment has the objective to

- create in a production environment conditions that guarantee a reproducible bond quality
- improve wetting and adhesion
- improve the long term stability of a bonded joint

Many plastics, especially thermoplastics have a low surface tension and require some kind of treatment prior to bonding. In case the low surface tension is caused by a contamination of the substrate, e.g. excessive release agent a simple cleaning process might be sufficient. If the low surface tension is related to the substrate's composition (e.g. non polar plastics like polyethylene and polypropylene) the surface needs to be activated in order to allow the formation of adhesion bonds between substrate and adhesive. Besides special primers and technologies like flame treatment and corona discharge the open air plasma technology is being utilized in the industry with good results.

Flame treatment consists of exposing the surface to a suitable oxidizing flame for a period in the range of 0.2 to 3.0 seconds. For a short term a surface temperature in the range of 200 – 400 °C is reached resulting in a change to the polymer surface by a free radical oxidation process that improves wetting and permits a strong adhesive bond between the surface and the adhesive. The functionalities introduced by oxidation are hydroxyl, carbonyl, carboxyl, and amide groups with a typical oxidation depth of approximately 4 to 9 nanometers

The major flame treatment parameters to be controlled if optimum flaming conditions are to be used are

- Gas/air ratio. This is dependant on the type of gas used (town gas, methane, propane and butane are suitable). A laminar flow flame is preferable to turbulent flame.
- Distance of the burner to the surface.
- Speed of the flame relative to the surface - Residence time of the surface in the flame.

In a **corona discharge process**, the plastic is exposed to a corona discharge, usually in the presence of air and at atmospheric pressure. This roughens the surface, which provides sites for mechanical interlocking, and introduces reactive sites on the plastic's surface, consequently increasing the wettability and reactivity of the surface. The reactive functionalities which are theorized to be introduced to the surface may include, but are not proven to be, carbonyl, hydroxyl, hydroperoxide, aldehyde, ether, ester, and carboxylic acid groups, as well as unsaturated bonds.

Process parameters are:

- Distance of the corona nozzle to the surface
- Speed of the corona nozzle

The **open air plasma process** can be seen as advancement to the common plasma technology. In contrast to the common technology which increases the bondability of a substrate by bombarding the substrate surface with ions of a gas, such as Ar_2, He_2, N_2, and O_2, at low pressure this novel technology works at atmospheric pressure and does not require a vacuum chamber. In the open air plasma process a high voltage discharge within a nozzle is used to create the plasma. A targeted gas flow along a discharge route separates parts of the plasma and transports these through a bezel on the surface of the material that is being treated.

Several mechanisms have been proposed to explain the enhanced bondability created by plasma treating. For example, plasma treatment is hypothesized to crosslink the substrates surface, which strengthens the joint boundary and prevents a thin layer of substrate from peeling off. In addition, the surface oxidation caused by plasma treatment is thought to introduce reactive functionalities which then increase the surface's reactivity and wettability.

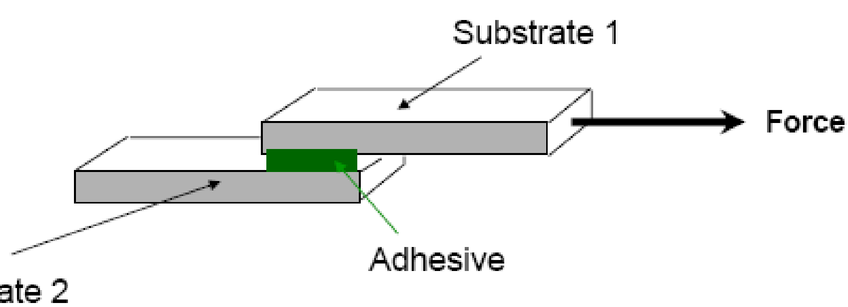
Process parameters are:

- Distance of the plasma nozzle to the surface
- Speed of the plasma nozzle
- Nature of the gas used; in most cases air is used. The use of other gases offers the opportunity of introducing special functional groups into the surface

TEST METHODS FOR PLASTIC BONDS

During the development of adhesives as well as in the evaluation of different adhesives for a particular application the use of standardized test methods is a necessity. This is the only way to get information on the short term and long term performance of an adhesive in different environments at a reasonable cost. There are established standardized test methods for the bonding of metal substrates. The very common lap shear test EN 1465 (fig. 4) and its US equivalent ASTM D 1002 are, as described in the scope to the test limited to metallic substrates: Nevertheless they are widely used in the industry also for other substrates like plastics. The US ASTM association has published with ASTM D 3163 a just slightly modified version for plastics.

Fig. 4:
Lap Shear Test, EN 1465,
ASTM D 1002, ASTM D 3163



Both the two ASTM methods as well as the EN standard are recommending 12.5 mm as length of the test area. This value originates from testing substrates with a Young's Modulus and a yield point similar to aluminum. In principle it would be necessary to adjust the length of the test area to the particular substrate. In all cases a failure inside the test area should be achieved (adhesive- or cohesive failure as well as delamination or fiber tear). Stock break, even relatively close to the test area is not very informative, simply by increasing the bond area the mode of failure can be influenced to happen outside the test area.

In addition to the well known effect of an uneven stress distribution (fig. 5) during lap shear testing a significant deformation of the test specimen as shown in fig 6 is very often observed during the lap shear testing of plastics. This results in a significant portion of peel forces affecting the bond. As peel forces do have a negative effect on the adhesion the results are depending on the degree of deformation and therefore on the mechanical properties of the plastic. If this is kept in mind and all tests have been carried out on the same plastic with the same thickness of the test specimens the lap shear test is a helpful tool during adhesive evaluation.

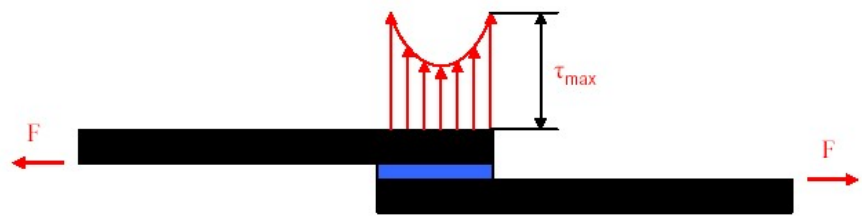


Fig. 5:
Lap Shear Test -
Uneven Stress [7]

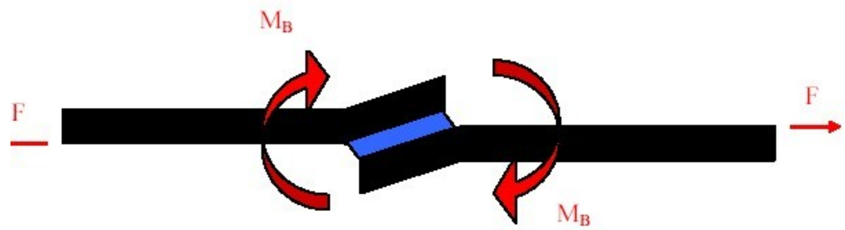


Fig. 6:
Lap Shear Test –
Deformation During Lap Shear Testing of Plastics [7]

In most cases the information about the adhesion performance (failure mode) to plastic materials is of more interest then the knowledge about the strength of a bonded joint. In order to differentiate either several adhesives on one particular plastic substrate or to find the best adhesive to bond to a particular plastic peel tests like the Cleavage Peel Test described by ASTM D 3807, (fig. 7) have been developed.

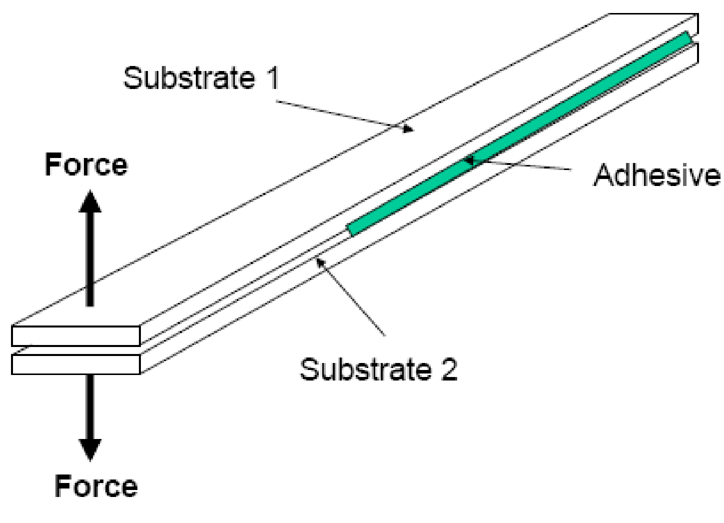


Fig. 7:
Cleavage Peel Test
ASTM D 3807

The objective of an ongoing research project at the University of Kassel is to fill the still existing gap in the standardization by developing a novel test to determine the mechanical performance of bonds of plastic materials [8]. Both the influence of the manufacturing process for plastic parts as well as the effect of a surface pretreatment should be analyzed and finally the ability to apply arithmetic techniques like FEM should be achieved.

ADHESIVE SELECTION

Adhesive selection for plastic substrates does not only include evaluating adhesion and strength within the appropriate temperature range but the mechanical properties of the substrates (strength, stiffness, Young's Modulus, elongation, …) as a function of temperature needed to be taken into account.

Due to the diversity of available plastics and their distinct properties a general statement in regard of adhesive selection is not possible. It can be assumed that the adhesive has to show a certain elasticity to compensate stress peaks emerging during use. The Young's Modulus of plastics is in most cases a few orders of magnitude lower then the modulus of metals, which in automotive engineering are more and more joined by adhesive bonding. For thermoplastics the modulus is highly dependant on the temperature and drops further as temperature is increasing. As a result the adhesive to bond such a plastic needs to show different properties then the adhesive to bond the same part, but made from metal. From the group of structural adhesives categorized by strength and modulus in fig. 8 the 2-part polyurethane adhesives are of special interest. They are well balanced regarding strength and elongation.

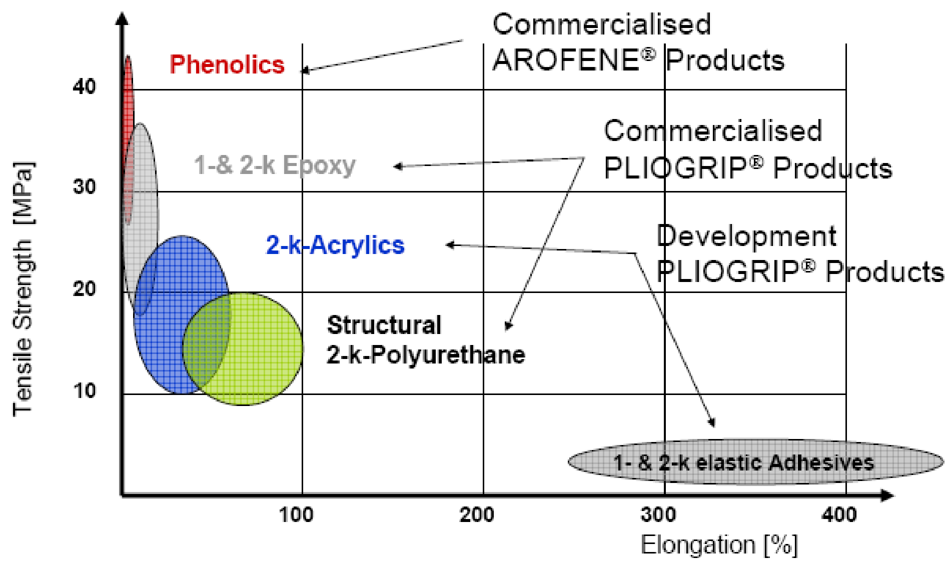


Fig. 8:
Structural Adhesives –
Mechanical Properties
by Technology

CASE STUDIES

Composite parts in automotive engineering do have a relatively long history. A concept for a full composite car (fig. 9) goes back to 1946. The car -- also known as the Stout Forty-Six -- was a dream car created by William Bushnell Stout, an automobile and airplane designer, and Games Slayter, then-vice president of research for Owens Corning Fiberglas. The two recruited the help of Granville artist and technician, Walter Krause, and worked secretly on the project in a Newark garage rented by Owens Corning Fiberglas. The car changed the way builders and designers viewed automobiles and achieved many firsts. It was the first made of Fiberglas-reinforced plastic -- which was supposed to be lighter and stronger than steel. It had the first wrap-around glass windshield to increase driver visibility. The front seats swivel to face the back -- "so dad could play Monopoly with the kids," suggested Paul Legris, The Works' exhibit developer. Also, the rear seat could be converted into a double bed, and there was room enough to set up a card table in the passenger compartment. Stout drove the automobile cross-country several times giving demonstrations. He traveled more than 250,000 miles. Today, the Project Y car is owned by the Detroit Historical Society Museum. [9[

The first commercial application for Ashland's PLIOGRIP® structural adhesive was the International Truck hood made from SMC in 1967 (fig 10). Since then more and more SMC parts have been introduced. A good example is the liftgate of the **French/Italian (Peugeot, Citroen, Fiat, Lancia) minivan family**. All four models share the same basic body, the individual exterior design is achieved besides others by different liftgates made from a SMC outer shell bonded to the inner reinforcement with a 2-part structural polyurethane adhesive. In order to minimize the surface preparation to just a simple wipe with a hydrocarbon solvent to remove dust a primerless heat accelerated adhesive system is used. The heat applied to the adhesive during the cure helps to form good anchorage of the adhesive on the SMC surface with the result that the bond is actually stronger then the parts bonded together. In destructive testing almost 100 % fiber tear is observed.

Fig. 9:
First Full Composite
Car Concept [9]

Besides all the different bonded thermoset composite parts (spoiler, trunk lid, front hood, deck lid, hard top, wing, etc) there are also some examples of CFRP parts bonded to become a integrated part of the body structure. As an example the transmission tunnel of **Aston Martin's Vanquish** is bonded to the aluminum body and acts as an important structural part within the body. In order to reduce the weight of the front of the Vanquish a CFRP part is used as crash structure just bonded to aluminum strut towers. Due to the small number of cars, ambient cure of the adhesive, offering both a sufficient open time and a fast cure response was an important requirement to the selected technology competitive against other technical approaches [10]. A very similar adhesive was later used to bond the carbon fiber roof of BMW's light weight sports car M3 CSL (fig.10) to the already painted metal body. Besides the general requirements of a sufficient strength to provide the required stiffness of the body also at elevated temperature together with a long open time of at least 25 minutes and maximum clamp time of 100 minutes was required [11].

Fig. 10:
BMW M3 CSL –
Bonding the CFRP
Roof to the Body [11]

During the mid nineties Chrysler started the development of **a concept vehicle (CCV)** to illustrate the advantage involved with the use of large injection molded thermoplastic body panels in automotive engineering [12]. Besides a significant weight reduction a significant cost advantage, mainly in assembly costs was achieved. The body (fig 11) in general consists of just 4 large composite parts made from fiber reinforced thermoplastic polyester. A two part polyurethane based structural adhesive with mechanical properties (modulus ~ 700 MPa, elongation ~ 50 %) assuring a good stiffness of the body together with the ability to compensate and withstand vibrations was selected to bond the parts forming the body.

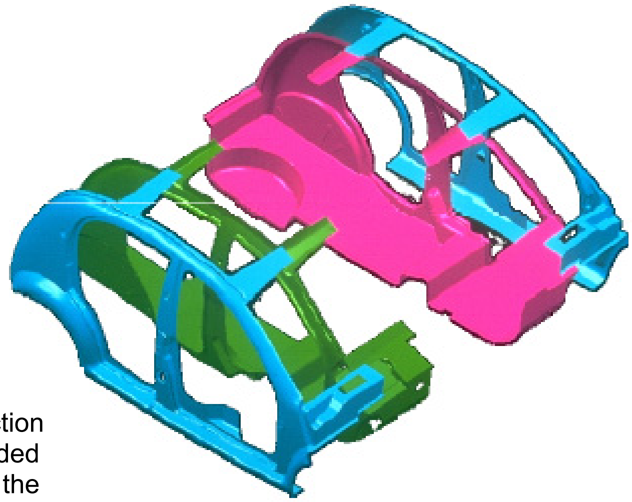


Fig. 11:
CCV – Large Injection Molded Parts Bonded Together Forming the Body [12]

As typical for a concept vehicle just a few unites have been build. Therefore the use of a heated fixture for heat accelerated cure of the adhesive could not be justified. Besides the standard requirements (adhesion, matching mechanical properties, good long term stability, etc.) one important requirement was the ability to cure at ambient temperature. This was achieved by using an isocyanate based primer for pre-treating the composite surface. In order to avoid any mechanical movement of the parts relative to each other the parts were secured during cure by a small number of bolts.

The overall very positive results of the concept vehicle:

- weight of the body of just 95 kg compared to 167 kg of a Audi A2 aluminum space frame body
- significant reduction of parts from about 4000 for a standard car body to about 1100, resulting in a
- significant reduction of assembly time from about 19 to just 6.5 hours and a
- resulting reduction of labour costs by 40 %

have led to the introduction of this technology into series production of the hard top for Chrysler Jeep vehicles.

Especially during the last years more and more thermoplastics are used to make automotive body panels. Main driver for thermoplastics vs. thermoset materials is the ease of recycling which as a result of the European End of Life Vehicle Directive has become very important. As the most benefit of a weight reduction can be get from reducing the weight of the car's front section with its heavy engine, more and more wings are made from light weight materials. This does not only lead to a reduced weight of the car but also helps to achieve a well balanced weight distribution with improved driving performance. As an example BMW is making the front wing of the 6-series convertible and coupe from PPE (polyphenylen-ether-polymer) reinforced polyamide with bonded reinforcements from the same plastic. On the other hand Volkswagen has selected PUR-RIM as material for the wing of the Tuareg, with app. 180 cars/day, Phaeton with app. 15 cars/day and Bentley with just 5 cars/day. The necessary bonded in reinforcement parts are made, depending on the model again PUR-RIM, PPE-reinforced PA, or e-coated steel (13).

In addition to the already mentioned general requirements it is important that the adhesive

- does not create any distortion in the surface
- withstands the paint cycle temperature of 20 minutes at 160 °C, followed by 45 minutes at 145 °C
- is suitable not only for the Tuareg production of 180 cars with an robotic process and the requirement to achieve a sufficient handling strength to allow a further handling within 40 minutes, but also for the low volume application for The Bentley with manual application and the resulting need of an open time of at least 8 minutes.

For both the BMW and the Volkswagen fender polyurethane adhesives adjusted to the specific production requirements are in use. BMW has selected open air plasma as surface preparation. In a first step the robot is using the plasma gun to prepare the surface of the parts along the bond line. After replacing the plasma gun by the adhesive dispensing and mixing head the adhesive is applied and finally the robot is placing the parts into the heated fixture for accelerated cure of the adhesive.

Volkswagen has selected a cleaning operation with n-heptane. Tests (fig. 14) have shown that a sufficient cleaning has been achieved as the solvent fully wets the surface which corresponds with an overall surface tension of ~40 mN/m with a polar part of ~5 mN/m. In production some problems occurred with insufficient

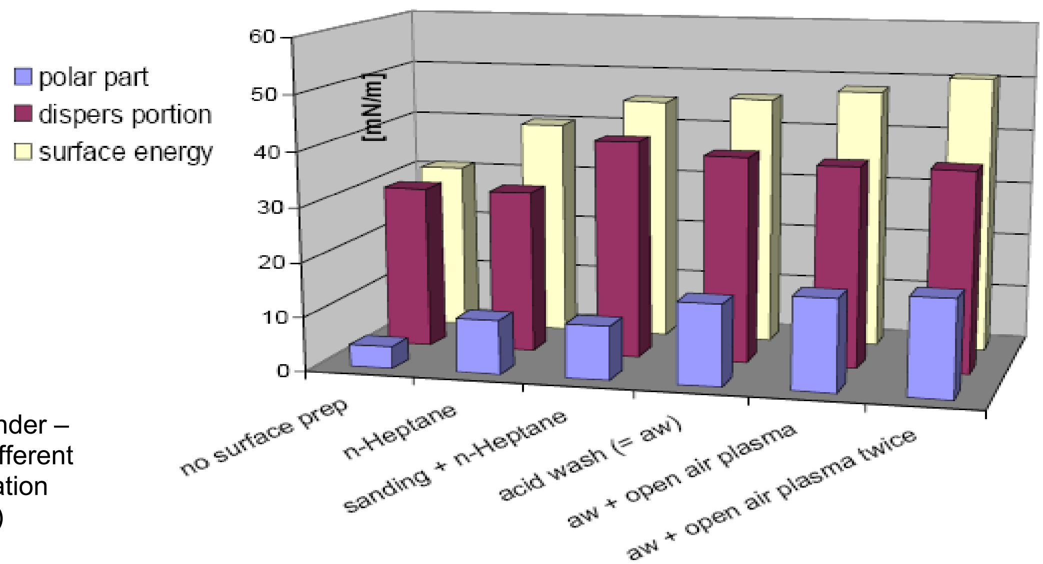


Fig. 14:
Volkswagen Fender – Evaluation of Different Surface Preparation Techniques (13)

adhesion in particular domains although the overall surface tension showed the desired values of close to 40 mN/m. A more thorough investigation of the adhesion related polar part of the surface tension showed enormous difference from below 1 mN/m in the problematic domains to about 4 to 5 mN/m for the domains showing good adhesion. This effect was caused by just having one injection point for the large wing. The release agent was therefore not uniformly distributed, to the end of the flow length a higher amount of release agent was detected then close to the injection point. Some slight adjustments in the injection parameters helped to solve this problem. This case is a good example to illustrate the importance of the surface for the quality of the resulting bond and also for the fact that the surface itself is, especially for injection molded thermoplastic parts depended to a certain degree on the manufacturing process. Evaluating adhesives on some test panels in the lab might give completely different results then obtained on real parts from series production.

Another effect repeatedly observed with bonding thermoplastic materials is the positive influence of a post bake to adhesion. It should be illustrated on the example of bonding glass fiber reinforced polyamide as it is currently under evaluation at different car manufacturers to replace metal for body panel applications (fig. 15). Lap Shear testing to evaluate different structural adhesive with a Young's modulus in the range of 5 to 700 MPa to bond this novel material showed after a heat accelerated cure of 3 minutes at 60 °C mainly adhesive failure with a strength of 2 – 7 MPa. A post bake of 20 minutes at 160 °C as it is typical for an automotive paint process resulted in a significant improvement of adhesion together with an increase in lap shear strength. Depending of the mechanical performance of the adhesive either cohesive failure for the low modulus adhesive or fiber tear for the high modulus adhesives was observed. The good performance was maintained also after exposure to an environmental cycle test (BMW RP 3081).

ELECTROMAGNETIC BONDING [14], [15], [16]

The electromagnetic bonding process does represent a technology combining bonding and welding in order to achieve highly reliable joints. Electromagnetic (or induction) welding of thermoplastics is a simple, rapid and reliable assembly technique that produces structural, hermetic or high-pressure seals for most thermoplastic materials. Fusion temperature at the abutting interface of the parts to be bonded is achieved by using a specially formulated thermoplastic resin to absorb energy provided by an RF induction field. The process is widely used for polyolefins and polyamide but not limited to such difficult-to-join materials. In addition to homogeneous polymers, the process can bond filled and/or glass fiber reinforced polymers to themselves or to selected dissimilar thermoplastics.

The welding process begins with placement of the lower half of the part in the press, followed by insertion of the susceptor material, and placement of the upper half of the part in the press. As illustrated in fig. 15, the parts are held in close alignment to the work coil that delivers the induction energy by suitable fixtures. During joining, low pressure is applied to the parts until the heating is sufficient for the susceptor compound to reach its melt temperature initiating flow, and then high pressure is briefly applied to assure that the final positioning of the parts is correct. After joining, the susceptor compound has filled the designed gap in the joint and fused the mating parts, resulting in a polymer-to-polymer permanent bond.

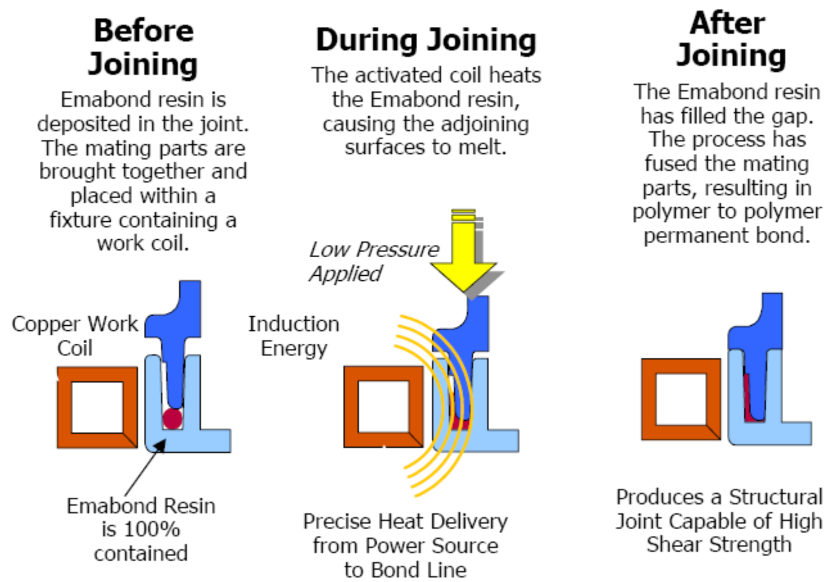


Fig. 15:
Electromagnetic Bonding -
The EMABOND® Process

The induction welding system includes an RF generator, application geometry specific work coils, an assembly press and tooling, the associated controls, the components to be joined, and the susceptor material. The key process interaction is that between the work coils and the susceptor material. The work coil can be thought of as an RF antenna and the generator is an RF transmitter. The generator/work coil system has to be tuned to perform properly. Although RF energy has the ability to propagate through air, it is known that the intensity of the field follows an inverse square function, so uniform heating is best achieved by maintaining a uniform distance between the work coil and the bondline. Very long bondlines are often a great challenge to other welding methods, but induction welding is ideally suited to such components. Work coils have been designed to weld very large parts or to weld multiple smaller parts simultaneously (coils for up to 20 individual welds performed simultaneously are in commercial use). Examples illustrating the many different areas of application in the automotive industry are shown in fig. 16.

Fig. 15:
Electromagnetic Bonding -
Areas of Application

CONCLUSION AND OUTLOOK

With the increasing use of plastic materials in automotive engineering and the development of novel plastics with improved performance, joining of such materials has become important and new adhesives with further improved performance have been developed. Although the universal adhesive for all plastic applications will still remain an engineer's dream, adhesive solutions to join most plastics are already available and can be used to fulfill the high-quality requirements of the automotive industry and a further increasing use of plastics, both staple articles like PP and engineered plastics will not be hindered by the lack of a suitable joining technology.

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