Joining plastics by adhesive bonding in automotive engineering

The use of composites in automotive engineering has increased. Further increases are expected, not only because of the weight-saving opportunities, but also for other reasons like design freedom. In many cases, the use of composites involves joining components together to form the final part. Adhesive bonding is playing an important role in this, of course.

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Besides the traditional interior applications, plastics are also being used for exterior applications these days. This will not remain limited to bumpers, spoilers, trunk lids and lift gates. Plastics will enter - or have already entered - into new applications like roof modules and front hoods where, barring some rare exceptions, thermoset materials like SMC and BMC have been used. The use of reinforced thermoplastics will certainly increase [1].

Low density and the weight-saving potential that results in improved fuel consumption are not the only reasons plastics are being used for a greater proportion of the material mix in a modern automobile. Another important benefit (besides their resistance to corrosion) is the styling freedom: shapes that cannot be made from metal can be made from plastics. In addition, plastics offer cost benefits for low-volume applications and for producing individual parts for high-volume models - for example, the lift gate on Peugeot, Citroen, Lancia and Fiat minivans.

Identifying and selecting a suitable joining technology for plastic materials is of special importance. Besides mechanical joining techniques that use snap fits, rivets, bolts and the like, bonding and welding (limited to thermoplastics) are of great importance. Because of the wide range of properties that are possible with all the different plastics, these are very attractive materials for all kinds of automotive parts. However, they also require careful selection of an adhesive system, as the specific requirements of the materials to be bonded, the bonding process itself, and the performance specifications for the final bonded part all have to be taken into account.

What is bonding?

Adhesion and cohesion [2], [3]

Bonding is defined as the 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; cohesion is the internal strength of a material, e.g. the adhesive.

A look at the cross section of a bond (Figure 1) shows that it 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. What the adhesive forces do have in common is a short range of about 0.1 to 0.5 nm;
- In the transition zone, the chemical, mechanical and optical properties of the adhesive alter. The thickness of this zone can vary from a few nanometres up to the millimetre range and depends on the adhesive and its cure conditions, and on the substrate;
- In the cohesion zone, the adhesive possesses its nominal properties.

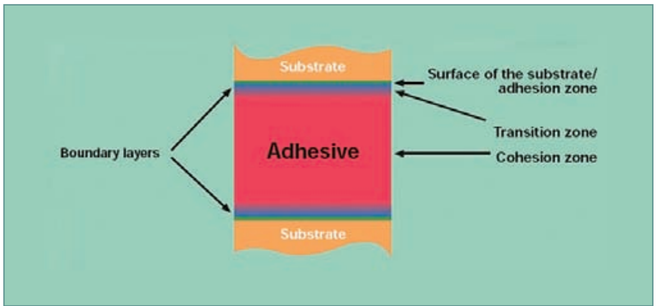

Fig. 1: Cross section of a bond [2]

With this as a given, it becomes obvious that all three layers play an important role in a bonded structure's performance. The strength of a bond, of course, is 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 adhesive and cohesive forces to environmental parameters like humidity.

Surface preparation [3], [4], [5], [6]

A prerequisite for forming an adhesive boundary layer (which consists of an adhesion zone and a transition zone) is a good wetting of the substrate by the liquid adhesive. Good surface wettability alone is not sufficient, however; adhesion also requires the formation of intermolecular interactions between substrate and adhesive.

Most cases require some kind of pre-treatment of the surface, maybe just a simple cleaning operation - e.g. dry wipe - to create a reproducible surface to which the adhesive can adhere. In general, a surface pre-treatment aims at:

- Creating the production-environment conditions that will guarantee a reproducible bond quality,
- Improving wetting and adhesion,
- Improving the long-term stability of a bonded joint.

Depending on the particular material to be bonded and the adhesive, a suitable surface preparation technology has to be selected.

Test methods for plastic bonds

For any particular application, the use of standardised test methods is a necessity during the adhesive development phase and in the evaluation of different adhesives. This is the only way to get information at a reasonable cost on the short- and long-term performance of an adhesive in different environments. There are established standardised test methods for the bonding of metal substrates. As described in the scope of the very common lap-shear test EN 1465 (Figure 3) and its US equivalent ASTM D 1002, these standards are limited to metallic substrates; nevertheless, they are also widely used in the industry for other substrates like composites. The US ASTM association has published a slightly modified version for plastics, the ASTM D 3163.

Both ASTM methods and 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 aluminium. 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 fibre 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 (Figure 2), a significant deformation of the test specimen is very often observed during the lap-shear testing of plastics, as shown in Figure 3. 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 depend upon the degree of deformation, and therefore on the mechanical properties of the plastic. If this is kept in mind and all tests are carried out on the same plastic using the same test-specimen thickness, the lap-shear test can be a useful tool during adhesive evaluation.

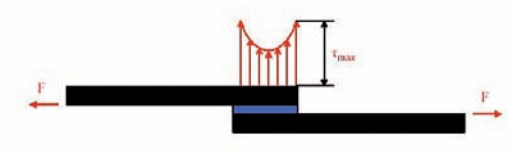

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Fig. 2: Lap-shear test - Uneven stress [7] distribution
Fig. 3: Lap shear test - Deformation during lap-shear testing of plastics [7]

In most cases, the information about the adhesive performance (failure mode) of plastic materials is of more interest than the knowledge about the strength of a bonded joint. Peel tests like the cleavage peel test described in ASTM D 3807 (Figure 4) have been developed to either find the best adhesive to bond to a particular plastic or to differentiate the adhesion properties of an adhesive to different plastic materials.

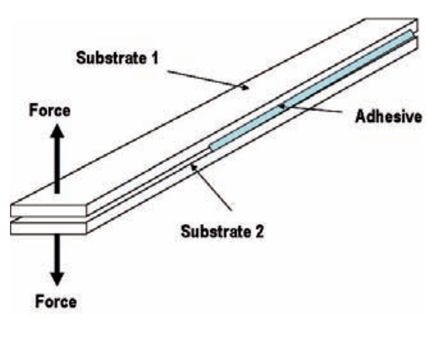

Fig. 4: Cleavage peel test ASTM D 3807

The objective of an ongoing research project at the University of Kassel is to fill the still-existing gap in standardisation by developing a new test for plastic materials to determine the mechanical performance of the bonds [8]. This research should establish the influence of the manufacturing process for plastic parts and the effect of a surface pre-treatment through analysis, and finally the feasibility of applying arithmetic techniques like FEM.

Adhesive selection

Choosing an adhesive for plastic substrates is not just a matter of evaluating adhesion and strength within the appropriate temperature range - it must also take into account the mechanical properties of the substrates (strength, stiffness, Young's modulus, elongation, etc.) as a function of temperature.
Due to the diversity of composite materials and their distinct properties, a general statement as regards 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. In most cases, the Young's modulus of plastics is a few orders of magnitude lower than the modulus of metals, which in automotive engineering are being joined more and more by adhesive bonding. For thermoplastics, the modulus is highly dependent on the temperature and drops further as temperature increases. As a result, the adhesive used to bond such a plastic needs to have different properties than does an adhesive used to bond an equivalent metal part. Within the group of structural adhesives categorized by strength and modulus shown in Figure 5, two-part polyurethane adhesives are of special interest for bonding composites as they are well balanced in terms of strength and elongation.
In addition to the already mentioned criteria for adhesive selection, other process-related parameters have to be taken under consideration, such as:

- Open time (maximum time between the application of the adhesive to the part and the joining of the parts),
- Cure response (time to reach the required strength for further handling of the bonded part),
- Cure conditions (ambient or heat-accelerated cure),
- Rheology of the adhesive (sag resistant to allow application to vertical parts vs. self levelling), and
- Colour, among others.

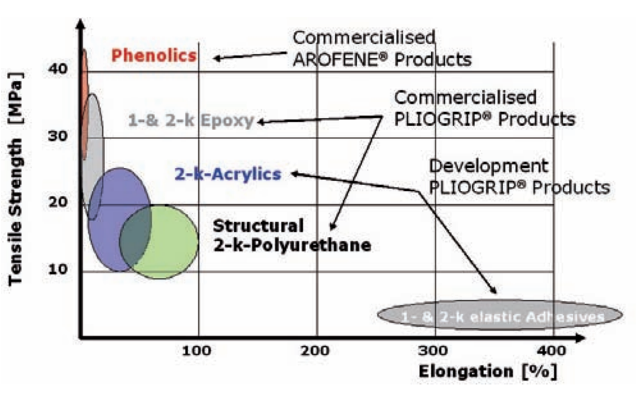

Fig. 5: Structural adhesives - Mechanical properties by technology

Case studies

Composite parts have a relatively long history in automotive engineering. A concept for a full composite car goes back to 1946. The car, known as the Stout Forty-Six, was created by Owens Corning Fiberglas. It was the first car made of fibreglass-reinforced [9] plastics, and changed the way builders and designers viewed automobiles.
The first commercial application for Ashland's PLIOGRIP® structural adhesive in the US was the International Truck hood made from SMC in 1967. The first European application was the trunk lid of Audi's legendary "Ur-Quattro" in 1984. Since then, more and more SMC parts have been introduced. A good example is the lift gate of the French/Italian minivan family (Peugeot, Citroen, Fiat, Lancia). All four models share the same basic body; the individual exterior design is achieved by different lift gates made from an SMC outer shell bonded to the inner reinforcement with a two-part structural polyurethane adhesive. In order to minimise the surface preparation to a simple wipe with a hydrocarbon solvent to remove dust and excessive release agent, a primerless heat-accelerated adhesive system is used. The heat applied to the adhesive during cure does not only accelerate the adhesive cure to achieve a short cycle time, but also helps to form good anchorage of the adhesive on the SMC surface, with the result that the bond is actually stronger than the parts bonded together. In destructive testing, almost 100% fibre tear is observed.
The most benefit of a weight reduction can be obtained from reducing the weight of the car's front section with its heavy engine. Therefore, more and more wings are made from lightweight materials to achieve a well-balanced weight distribution with improved driving performance. Examples are Aston Martin's D9 and Renault's Clio V6, both having SMC fenders; BMW's 6-Series convertible and coupe with fenders from PPE (polyphenylene-ether-polymer) reinforced polyamide; and Volkswagen's Tuareg, Phaeton and Bentley with a PUR fender. The reference to literature 13 which has to be changed to 12 as the original 12 (Reinforced Plastic reference needs to erased. All these parts require reinforcements, which are also necessary to assemble the fender to the body. For all fenders, polyurethane adhesives adjusted to the specific production requirements are used. The two SMC fenders and the Volkswagen fenders are manually cleaned prior to bonding by a solvent wipe process, while BMW has selected open-air plasma as surface preparation. In a first step, the robot uses the plasma gun to prepare the surface of the thermoplastic parts along the bond line. The plasma gun is replaced by the adhesive mixing and dispensing head and the adhesive is applied, and the robot then places the parts into the heated fixture for accelerated cure of the adhesive.

Besides all the different bonded composite parts (spoiler, trunk lid, front hood, deck lid, hard top, wing, etc.), there are also some examples of CFRP parts bonded to become an integrated part of the body structure. As an example, the transmission tunnel of Aston Martin's Vanquish is bonded to the aluminium body and acts as an important structural part within the body. To reduce the weight of the front of the Vanquish, a CFRP crash structure is used to carry systems like the cooler, etc. To assemble it to the car body it is bonded to aluminum strut towers after the engine has been assembled. to the body without the help of any without the involvement of any mechanical fastening (fig. 6). Due to the small number of cars produced, an ambient curing adhesive offering both a sufficient open time and a fast cure response was selected [10]. A very similar adhesive was used later to bond the carbon-fibre roof of BMW’s lightweight M3 CSL sports car (Figure 7) to the already painted metal body. Again, an ambient curing adhesive was selected, allowing both manual application and a relative fast strength build in order to achieve handling strength in a reasonable timeframe [11].

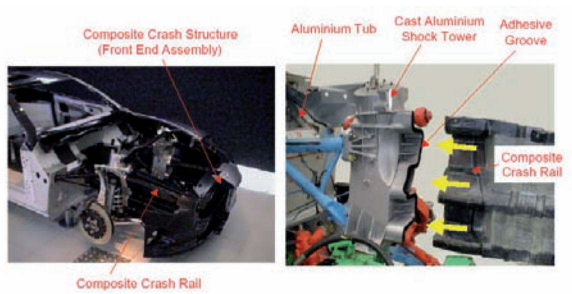

Fig. 6: Aston Martin Vanquish - Front assembly bonded on after engine installation [10].

Fig. 7: BMW M3 CSL - Bonding the CFRP roof to the body [11]

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 still remains an engineer’s dream, adhesive solutions to join most plastics are already available and can be used to fulfil the high-quality requirements of the automotive industry and support further growth in the use of plastics. ■

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