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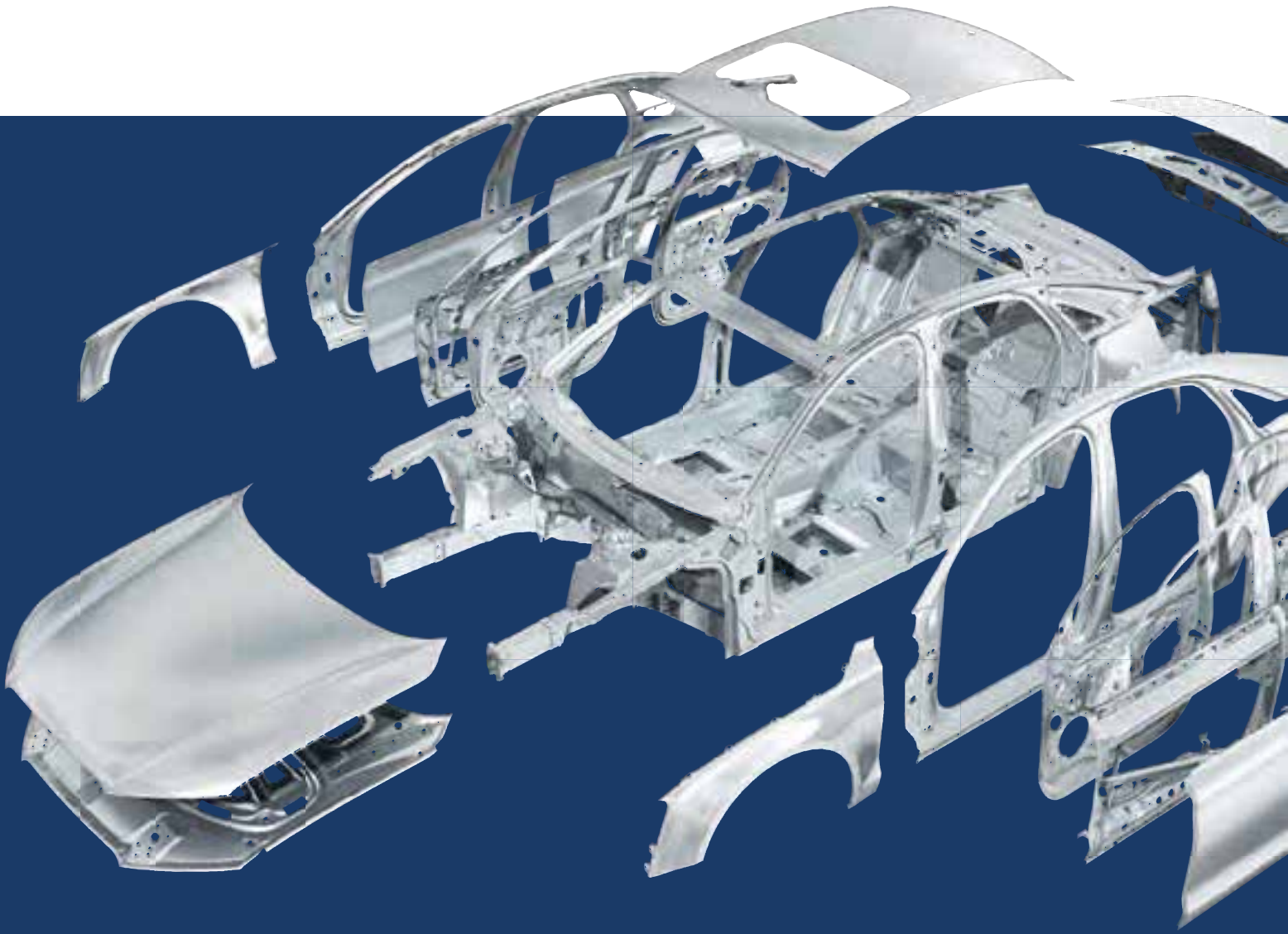
DGE GROUP

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STRUCTURAL BONDING OF LIGHTWEIGHT CARS
CRASH DURABLE, SAFE AND ECONOMICAL



Automotive Systems



„Without the use of bonding technology, modern lightweight designs would hardly be feasible – especially when it comes to bonding dissimilar and/or new materials.“

Dr. Andreas Groß, Advanced Training and Technology Transfer, Fraunhofer IFAM



EDITORIAL

Bonding Technology Meets Lightweight Construction

Dear Readers,

The automotive industry has in recent years successfully attempted to build lighter vehicles with more fuel-efficient engines in order to significantly reduce fleet consumption in accordance with legal requirements. Significantly lower fuel consumption and CO₂ emissions have been the immediate pay-off of such developments.

Improved fuel consumption, environmental friendliness, driving comfort, and safety therefore feature among the sales arguments many car manufacturers now employ for their marketing strategies.

Automotive suppliers and material manufacturers support car makers in developing modern lightweight designs and respond to questions concerning the potentials of current technologies and materials to satisfy challenging future requirements.

In this context, industry experts assume that steel will remain the primary material for vehicle structures. However, new high strength steel grades are finding their way into vehicle structures. Metals with low density such as aluminium and even magnesium are increasing in demand – as are polymer materials such as fibre-reinforced composites.

Fuelled by the importance of those very diverse materials, questions regarding bonding technology enter centre stage of the discussion. This is the key interface between lightweight construction and bonding technologies for new vehicle designs.

Modern lightweight designs require new bonding technologies in addition to new materials and/or an increased material mix. Bonding is of special importance here. It enables the use of new materials, new material combinations and it provides structural advantages for bonded components.

Please review the following technical summary to learn more about the status quo of existing concepts as well as new potential development in adhesives and foams for use in modern light weight vehicle construction.

I wish you a fascinating read and successful bonding!

Dr. Andreas Lutz
Head Developer “Metal Bonding Europe”
Dow Automotive, Horgen, Switzerland

THE KEY TO MAKING LIGHTWEIGHT CARS



STRUCTURAL ADHESIVES

Modern lightweight designs require new bonding technologies in addition to new materials and/or an increased material mix. Bonding is of special importance here. It enables the use of new materials, new material combinations and it provides structural advantages for bonded components.

1 INNOVATIVE LIGHTWEIGHT DESIGNS IN VEHICLE DEVELOPMENT

1.1 WEIGHT REDUCTION FOR MEETING FUTURE LEGAL STANDARDS

Two main factors drive vehicle weight reduction. In addition to the future maximum values for CO₂ emissions as expressed in the EU Directive 443/2009, an increasing number of countries are planning road usage fees based on such emissions. Both factors in combination with increased fuel prices result in a strong motivation to purchase low emission vehicles.

Fuel consumption can be lowered by a number of different methods. Lightweight vehicle construction is a significant factor throughout, immediately contributing to reducing fuel consumption. Savings by downgauging vehicle components such as powertrain, engine, and underbody yield further secondary effects. Various studies show that a 100 kg weight reduction results in reduced emissions of 5.0 to 12.5 g of CO₂ (ca. 3 to 7 %) per driven kilometre.

Representing approximately 40 % of total vehicle weight, the car body is the heaviest vehicle element. The consequent implementation of lightweight measures in the car body appears therefore very effective. Increasing demands regarding stiffness, acoustics, crash performance and long-term stability are generally in conflict with lightweight construction and underline the complexity of this challenge.

1.2 CURRENT TRENDS FOR REDUCING VEHICLE WEIGHT

Several methods for weight reduction are available. The three most important approaches are:

1. Use of low-density materials

Aluminium, magnesium and plastics/thermoset composites are often used in mounted parts and covers. According to a statement by the Aluminum Association Inc., aluminium contributed to an average of 7.8 % of the total weight for passenger vehicles in the year 2009.

2. Targeted use of high-strength materials

High- and highest-strength steels are solutions for wall thickness-reduced components. Tailored welded or tailored rolled-blanks are related technologies that make use of this principle.

3. Integrated lightweight construction

This is a combination of various materials and functional characteristics based on the use of bonding technologies and production processes.

The most significant lightweight construction trend over recent years is the use of high-strength steels (HSS). Even vehicle bodies of the European compact car class now contain a HSS share of 50 to 65 %. Without exception, the safety cells of today's cars consist mainly of HSS. Tailored welded or tailored rolled blank technologies are consequently used for further optimisation.

Another significant trend is the use of thermoplastics and thermoset composites in bonded roof components, hoods, trunk

covers and some body structure components. As the article will describe in further detail, bonding technology could also solve the challenge of joining various metallic and non-metallic materials.

1.3 THE PATH TOWARD A BALANCED CAR BODY

As mentioned above, reducing the body weight, while simultaneously increasing performance, is a complex task. The following elements are key demands when developing innovative solutions:

1. Increasing the static and dynamic stiffness to improve the general vehicle quality and to optimize driving and handling characteristics.
2. Reducing vibrations and noise (noise, vibration, harshness and acoustics).
3. Optimising crash behaviour to comply with legal and voluntary safety guidelines (EG: NCAP safety testing)
4. Extending vehicle lifespan and long term value via higher quality and retained driving characteristics.

Improvements in those four areas are by no means the only challenges when reducing vehicle weight. A new vehicle generation often requires the development of greater passenger space. Consequently, new vehicle models are rarely lighter than their predecessors.

1.4 POTENTIALS AND LIMITS OF CURRENT TECHNOLOGY TRENDS

Five years ago, mild steel contributed between 40 and 50 % of the body shell weight. Today, new vehicles generally contain a mild steel share not exceeding 20 to 25 %. Further materials include mostly high-strength steels and, increasingly, aluminium. Using high- and ultra high- strength steels allowed wall thicknesses reduction up to 0.5 mm. It is however unlikely that such steel grades can further increase the structural optimisation potential.

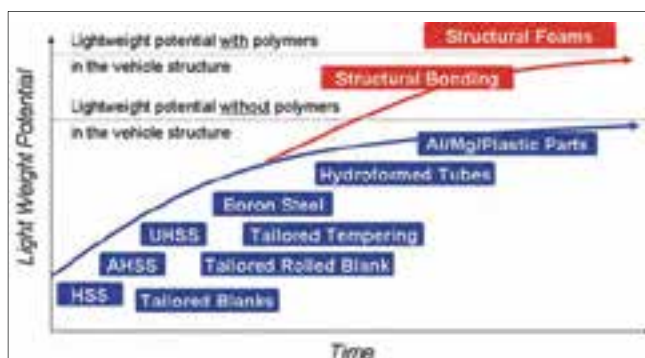


Figure 1 New weight reduction potential with structural adhesives and structural foams

Particular weight reduction measures such as tailored welded or tailored rolled blanks have in the meantime also become a standard in compact cars. When considering the strongly rising aluminium share on top of that, it becomes clear that additional new technologies will be required to further reduce weight.

2 STATUS QUO OF STRUCTURAL BONDING IN THE VEHICLE BODY

Structural adhesives and structural foams (see chapter 5) are polymer solutions offering a great potential for body weight reductions: Figure 1.

Such technology concepts allow for additional performance improvements even in already-optimised body structures. These methods will be explained in more detail below.

2.1 STRUCTURAL BONDING OF UNCOATED METAL SUBSTRATES

Structural bonding signifies permanent and stable bonding increasing the overall efficiency and effectiveness of a conventionally joined structure. For current automotive metal bonding applications more than 95 % is based on epoxy adhesives. This is due to the combination of various advantageous characteristics such as oil absorption capacity, durability, and outstanding mechanical characteristics across a wide temperature range.

Structural bonding in vehicle construction is used in the following areas:

- Joining non-weldable and/or heat-sensitive components and materials.
- Construction components that are hard, or impossible to access with welding devices
- Joining various metallic and non-metallic substrates with regard to avoiding galvanic corrosion.
- Reducing cycle times and costs by reducing spot-welds

From experience, the use of structural bonding allows the following general performance characteristics:

- Increasing static stiffness between 8 and 15 %.
- Increasing dynamic stiffness by 2-3 Hz
- Increasing joint durability by 100 up to 10.000 %

Special impact resistance-modified epoxy structural adhesives – so-called crash durable adhesives (CDA) – yield additional load path-optimisation, thus further improving a vehicle's crash behaviour. Unnecessary performance potential can often directly be used for further reducing weight by downsizing the involved structures.

In addition to the established epoxy systems, innovative rubber-based structural adhesives with glass transition temperatures of over 90° C are becoming increasingly popular due to an attractive cost-benefit ratio.



Figure 2 Potential application areas of bonded hybrid composites

2.2 STRUCTURAL BONDING OF COMPOSITE MATERIALS

When joining composite components mainly two-component polyurethane adhesives (2K-PU) are used. Polyurethane adhesives are characterized by high strength and stiffness values at high elongation levels. This results in very positive impact and fatigue properties of bonded joints.

The use of bonded composite components offers the following advantages:

- Significant weight savings compared to conventional designs
- Design and functional integration lead to a reduced number of components
- Lower tooling costs compared to metal pressings and thermoplastic welding technologies
- High damage tolerance compared to aluminum and steel materials
- Very good corrosion resistance

As shown in Figure 2 composites are frequently used in hoods, trunk lids, hang on parts and floor applications.

PU-based structural adhesives allow joining these components in the vehicle assembly. To meet different requirements, numerous adhesive systems are available. Compared with conventional joining techniques a number of key aspects must be considered when selecting a structural adhesive:

- Consideration of assembly directions, joining and curing times

- Joint geometry and material selection correlates with load case
- Possible required surface preparation
- Dissimilar thermal elongation coefficients
- Stress/strain limitations

Advanced structural adhesives will help to optimize strength and elongation levels of bonded composite components and create new applications for crash-relevant components.

3 TRENDS WITH STRUCTURAL BONDING OF NON COATED METAL SUBSTRATES

Over the last ten years, crash durable adhesives (CDAs) have developed from a regionally applied adhesive technology into a globally applied solution. They are mainly used for vehicle structures and hem flanges for closures. Their positive contributions, which have by now become known and acknowledged, have improved several car characteristics, such as higher stiffness, improved crash performance and enhanced durability. The CDA technology furthermore enables the development of lighter structures and bonding of new materials such as ultra high-strength steel or composites. Future regulations will not necessarily require the development of new formulations, as today's products already provide first-rate mechanical performance levels. The future will therefore rather be about developing materials that further improve application and processing.

3.1 NEW REQUIREMENTS FOR STRUCTURAL ADHESIVES

Crash durable structural adhesives are globally used in the vehicle body structure. The market demands robust technologies that must meet the most diverse process requirements as outlined below:

Bonding galvanised steels

Today, many different steel grades are used in vehicle construction and the share of high- and ultra high-strength steels is peaking. The surfaces of those steels are usually galvanised. One disadvantage of such coating in combination with higher strength steels is its tendency toward layer delamination under strain. Crash durable structural adhesives bond those steels very effectively and significantly increase the durability of the joint, when compared to traditional methods such as spot welding.

Bonding of galvaneal steels

Crash-resistant structural adhesives bond very well to hot-dipped and electrolytically galvanised coatings. However galvaneal coatings have a layer delamination tendency under strain even for lower grades of steel. The development of special structural adhesives is therefore necessary.

Optimal temperature resistance

Adhesives are nowadays widely used in different global climate areas. In many cases they are stored for many months prior to application and constant storage conditions cannot be guaranteed. Independent of these storage conditions and modern application-critical processes like jet-spraying, the adhesive should under all circumstances be easily applicable. For this purpose high temperature-stable crash durable adhesives have been developed.

Optimal processability: good adherence, compressibility and gap filling

Good initial tack is necessary for oily metal substrates. This especially applies during winter when surfaces can become colder than 15° C and the drawing oil has a greater viscosity. Good adhesion must also be ensured on the opposite metal surface. When joining the components, the adhesive must have a good flow and squeeze behaviour in order to optimally fill gaps. Components such as doors rarely have constant gap dimensions. The adhesive must be able to fill the spaces resulting from those gap variations. The adhesive's rheology must be perfectly tuned to the process requirements.

3.2 MODERN CRASH DURABLE EPOXY ADHESIVES FOR STRUCTURAL BONDING

In the meantime, new CDAs have been developed meeting all of the above requirements and being ready for global supply.

	New generation crash durable adhesive	Former generation adhesive
E-Modulus [MPa], ca.	1500	1600
Elongation at break [%], ca.	20	13

Table 1 Adhesive nominal values comparison of former and new generation crash-resistant structural adhesives

Bonding high- and ultra high-strength steels

Compared to previous generation structural adhesives (see Table 1), new generation adhesives show greater elongation at break, reduced bonding strength loss after corrosion, and reduced loss of dynamic peel strengths at lower test temperatures and for higher strength steel grades.

Figure 3a shows the stability of impact peel values of various steel grades at test temperatures between +23° C and -40° C. Compared to former generation structural adhesives, the loss in

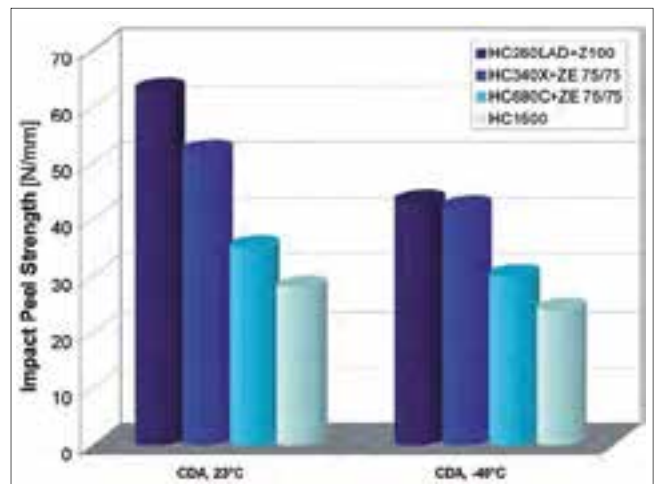


Figure 3a Impact peel strength depending on steel grades and test temperatures

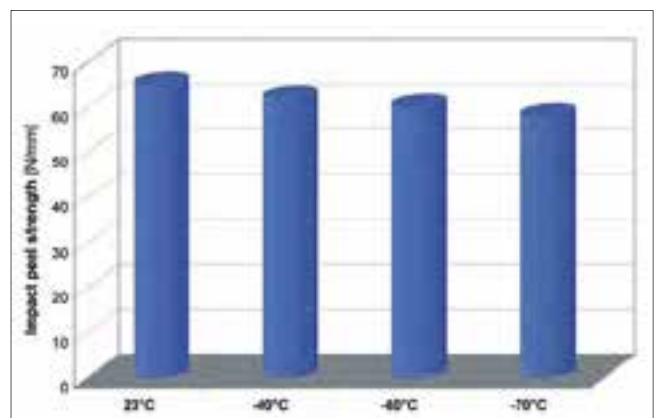


Figure 3b Impact peel strength for various test temperatures

impact peel strength is very low for higher strength steel grades and at low temperatures. The improved flexibility of the new generation adhesives is evident in Figure 3b displaying the impact peel strength of bonded steel samples of medium strength at various temperatures below 0° C. Even at temperatures below -40° C, the values remain remarkably high. In addition, these adhesives display an excellent corrosion resistance.

Bonding galvanneal coated steels

Bonded galvanneal coatings have a tendency towards delamination under strain. This tendency is greater for shear loads compared to peel strains. The new generation crash durable structural adhesives display a robust cohesive failure mode on galvanneal surfaces without impacting quasi-static shear and dynamic peel strengths.

	New generation crash durable adhesive	Former generation adhesive
E-Modulus [MPa], ca.	1400	1600
Elongation at break [%], ca.	12	13
Impact peel strength*[N/mm]	32	21
Shear strength [MPa]	23	22

*Impact peel strength SCGA 270, 1 mm; shear strength SCGA 270, 1,6 mm

Table 2 Adhesive characteristics and mechanical characteristics for a galvanneal-optimised adhesive .

Table 2 summarises the results of the new generation adhesive and compares this material to a former generation adhesive. Adhesive characteristics and shear strengths are comparable but dynamic impact peel strengths have significantly improved.

Temperature-resistant adhesives

The new generation adhesives display excellent temperature resistance up to 60° C. They can therefore be stored and processed for very long periods of time. The viscosity increase over time is extremely low and enables a shelf life up to twelve months. Figure 4 illustrates the viscosity increase over time as a function of the storage temperature.

Optimised Rheology for optimal adhesion, squeezability and gap filling

The rheology for new generation crash durable adhesives has been further optimized to the processing requirements. The new generation adhesives are shear rate dependent, displaying lower viscosity at higher shear rates and higher viscosity at lower shear rates. This has positive effects on the initial tack to oily metal substrates as well as on the adhesive's pumping characteristics, its squeezability and gap filling capability. The latter results in good gap bridging and geometric stability of the adhesive bead.

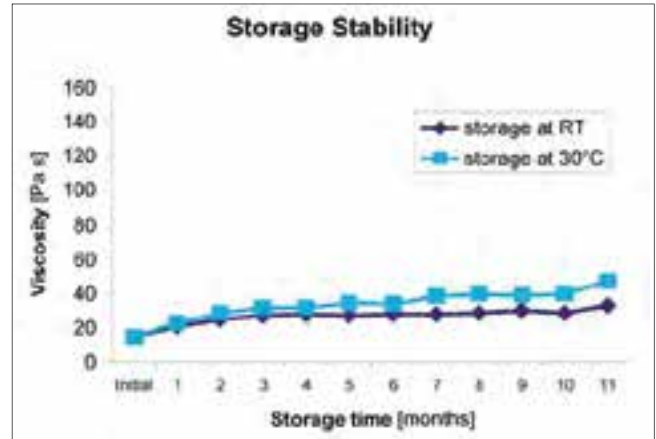


Figure 4 Viscosity increase over time

3.3 HIGHLY FLEXIBLE EPOXY ADHESIVES FOR HYBRID BONDING

Many closures are bonded with low modulus rubber-based adhesives. These adhesives however show various disadvantages over epoxy adhesive systems. The static and dynamic strengths are significantly lower than epoxy adhesives and they are generally less corrosion resistant. The glass transition temperature is situated within the operating temperature range of the vehicle.

The generally higher E-modulus of epoxy resin-based structural adhesives can result in read through effects when bonding exterior panels. A low-modulus adhesive can prevent such issues. Read through becomes an increasing issue since sheet thicknesses have continuously decreased over recent years.

A very flexible epoxy resin adhesive with low modulus has been developed for this application. It possesses significantly higher static and dynamic characteristics than rubber-based adhesives. The dynamic characteristics even match the levels of the crash-resistant structural adhesives.

The new adhesive technology unites sealing and reinforcing characteristics in a single product.

Table 3 summarises the characteristics compared to current structural adhesives. The E-modulus is significantly lower and the

	New generation crash durable adhesive	Former generation adhesive
E-Modulus [MPa], ca.	400	1600
Elongation at break [%], ca.	40	13
Impact peel strength[N/mm]	48	46
Edge shear strength [MPa]	15.4	19.6

Table 3 Performance comparison between the flexible and a traditional structural adhesive

elongation at break clearly better. The values for the mechanical characteristics are equal or slightly lower. In total, the performance level is significantly greater compared to rubber-based adhesives.

4 TRENDS IN STRUCTURAL BONDING OF COMPOSITE MATERIALS AND COATED METAL SUBSTRATES

4.1 DEMANDS ON BONDING SYSTEMS FOR COMPOSITE MATERIALS

The motivation factors detailed earlier for reducing vehicle weight have also resulted in a closer consideration of composite materials as a lightweight solution for traditional metal applications. Roofs, hoods, rear lids, and exterior claddings of future hybrid and electric vehicles will provide particular growth potentials for the use of composite materials. These applications are suitable for weight reduction in electric vehicles since such vehicles can be up to 200 to 300 kg heavier due to construction- and component-related requirements.

In order to insure optimum use of new innovative lightweight materials, innovative adhesive technologies capable of creating stable structures and withstanding high static and dynamic loads under various driving conditions will be necessary. The integration of composite materials and plastic bonding in vehicle production processes requires systems with very short hardening times. Simultaneously, less temperature-dependant strength and stiffness behaviours are necessary since the traditionally applied PU two-component systems possess a glass transition temperature within the vehicle operating range. High performance structural bonds will be needed that are able to cope with varying part tolerances when joining dissimilar materials and with differing joint geometries.

4.2 NEW GENERATION OF "TEMPERATURE-INDEPENDENT" PU HIGH-PERFORMANCE ADHESIVES

New primerless adhesives have been developed as a credible alternative to traditional bonding technologies for composite materials. These systems allow bonding of various materials such as SMC or carbon fibre reinforced plastics to coated metal substrates (steel or aluminium). This new generation of adhesive systems provides developers and design engineers new opportunities:

- Increased stability of modulus and strength values across a broad temperature range (-45 to +180° C)
- A high level of strength and elongation, independent of the bond thickness
- Improved aging performance
- Significantly lower bonding times through optimized curing behaviour – with cycle times of less than 60 seconds.

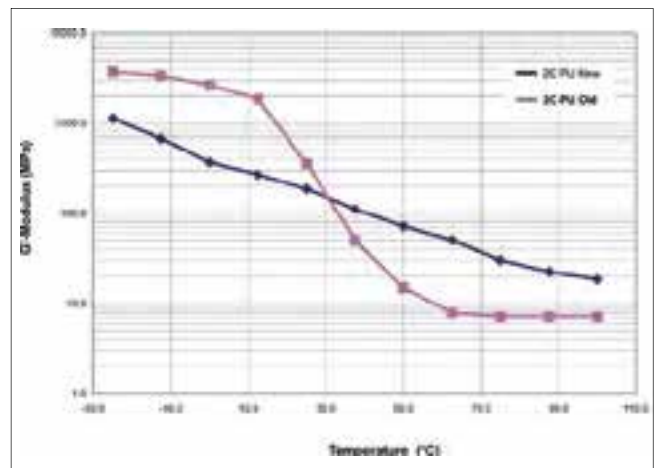


Figure 5 Modulus over temperature for existing and new structural PU Adhesives

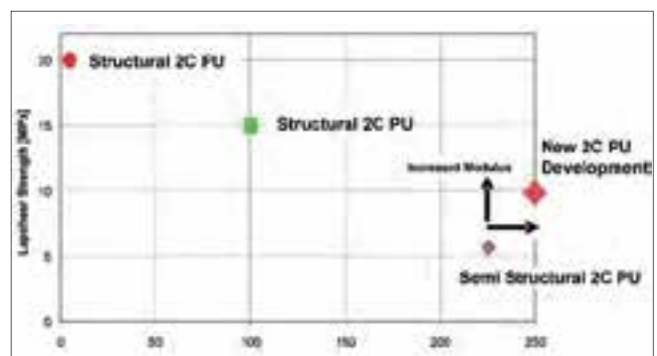


Figure 6 Strength and elongation properties of structural PU Adhesives

Newly developed polyurethane adhesives provide outstanding shear strength at high temperatures. The chart in Figure 5 directly compares a traditional PU adhesive with a newly developed PU adhesive.

The chart in Figure 6 illustrates the exceptionally high shear strength of newly developed polyurethane adhesives with simultaneous high elongation.

5 REINFORCEMENT FOAMS FOR BODY CAVITIES

For several years, vehicle engineers have been able to use reinforcement solutions from thermoplastic and thermoset materials during body development. The structural foams presented here are two-component polyurethane (PU)-based reinforcement materials. They are applied directly in body cavities at the production line in order to avoid unwanted dents and buckles in certain areas. Immediately following application, the expanded foams harden inside the cavity. Depending on the foam system, hardening will be completed after only a few seconds. The foam densities vary in structure-relevant applications, ranging from 200 to

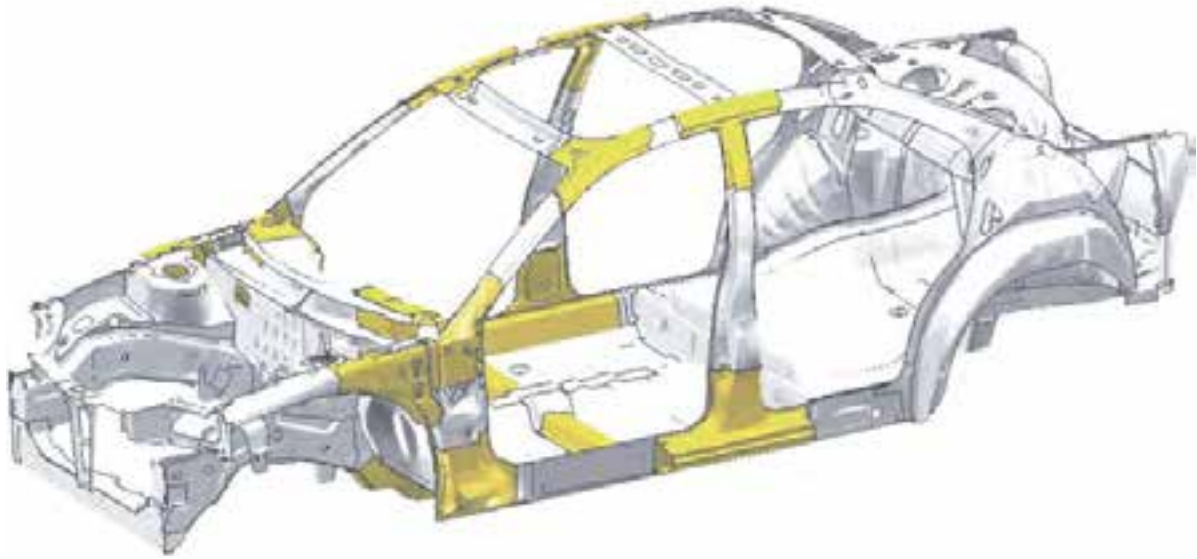


Figure 7 Structural foam applications to the vehicle body

600 g/l. Usually, structural foams are applied to surfaces which are already corrosion-protected, in order to achieve the greatest possible adhesion between foam and surrounding structure.

Figure 7 illustrates usual application locations of structural foams at the body shell's nodal points

PU foams provide the additional advantage of very quick processability while allowing the targeted adjustment of the structural performance of a body platform. Traditional metal reinforcements can often be replaced in a weight- and cost-optimised manner. Such systems can also quickly and easily be adjusted to new requirements, such as design changes. A development engineer can directly fine-tune characteristics such as body stiffness, crash performance, and acoustic performance via foam density and injection volume.

We can summarise the performance characteristics as follows:

- Increasing the crash and stiffness levels and/or using this increase toward weight reduction
- Advantageous system costs: the costs for a local reinforcement are mainly driven by the low structural foam material costs.
- Design freedom: No cost-intensive foaming tools required since directly applied to body cavities.
- Scalability: A single lean platform allows formation of different structural derivatives by varying foam density and injection volume. This will meet the targeted demands regarding configuration and other performance requirements.

6 SUMMARY

Epoxy resin and polyurethane structural adhesives have become indispensable components of modern car construction. Originally, such materials served to increase crash performance and long-term durability. From a current perspective however, lightweight body construction has become a primary consideration. This includes also the substrate mix, i.e. the combination of vari-

ous metallic and non-metallic materials where structural adhesives are used for many different applications. The continuous development of bonding systems will ensure that novel substrates can be bonded with optimized safety and durability in the future as well.

Locally effective structural foams complement the lightweight construction potential of such adhesives and furthermore provide substantial advantages with regard to flexible design and manufacturing of different vehicle variations. Unwanted bending and buckling behaviour in the vehicle structure can be prevented in a targeted manner. Load paths can thus be effectively optimised.

Natural resource shortages and environmental protection were the initially mentioned reasons for the societal and legislative drive towards lightweight design. The current need for lighter vehicles is very high and will without doubt increase over the coming years. Ultimately however, all lightweight construction measures must be guided by consumer behaviour and the evolution of fuel prices.

Epoxy resin and polyurethane structural adhesives provide wide ranging benefits of relevance to many key factors of interest to consumers, apart from weight reduction, (e.g. safety improvement and noise reduction) and will certainly continue to increase in use and application for future vehicle designs. ●

PRODUCT OVERVIEW

APPLICATION AREA	TYPE	PRODUCT NAME	PRODUCT CODE	CHEMICAL BASE	CURING	CHARACTERISTICS	CAE MODEL
Body shop, oily metal	Structural adhesive	Betamate™	1496	1 component epoxy	e-coat oven	Crash stable, vehicle structure	validated
Body shop, oily metal	Structural adhesive	Betamate™	1480	1 component epoxy	e-coat oven	Crash stable, hem flange and vehicle structure	validated
Body shop, oily metal	Structural adhesive	Betamate™	1620	1 component epoxy	e-coat oven	Crash stable, vehicle structure, jet sprayable	
Body shop, oily metal	Structural adhesive	Betamate™	1460	1 component epoxy	e-coat oven	Crash stable, vehicle structure, wash off resistant	
Body shop, oily metal	Structural adhesive	Betamate™	1485	1 component epoxy	e-coat oven	Crash stable, vehicle structure, low temperature cure	
Body shop, oily metal	Structural adhesive	Betamate™	1820	1 component epoxy	e-coat oven	Crash stable, vehicle structure, HSS optimized	available
Body shop, oily metal	Structural adhesive	Betamate™	flex	1 component epoxy	e-coat oven	Crash stable, hem flange, highly flexible	
Body shop, oily metal	Structural adhesive	Betamate™	1025	1 component epoxy	e-coat oven	Semi-crash stable, hem flange, low viscosity	validated
Body shop, oily metal	Structural adhesive	Betamate™	1040	1 component epoxy	e-coat oven	Semi-crash stable, vehicle structure, high viscosity	validated
Body shop, oily metal	Structural adhesive	Betamate™	1060	1 component epoxy	e-coat oven	Semi-crash stable, vehicle structure, wash off resistant	available
Body shop, oily metal	Structural adhesive	Betamate™	5103-2	1 component epoxy	e-coat oven	Structural applications, cold applicable	
Body shop, oily metal	Structural adhesive	Betamate™	1005	1 component epoxy	e-coat oven	Structural hem flange applications	
Body shop, oily metal	Structural adhesive	Betamate™	5096	1 component rubber	e-coat oven	Semi-crash stable, vehicle structure	
Body shop, oily metal	Structural adhesive	Betamate™	2096	2 component epoxy	ambient	Semi-crash stable, vehicle structure, repair	
Body shop, oily metal	Structural adhesive	Betamate™	2098	2 component epoxy	ambient	Crash stable, vehicle structure, repair	
Body shop, oily metal	Structural adhesive	Betamate™	2092	2 component epoxy	ambient	Semi-crash stable, vehicle structure, repair, fast cure	
Body shop, oily metal	Structural adhesive	Betamate™	2080	2 component epoxy	elevated (120°C)	Semi-crash stable, vehicle structure	
Paint shop, before wax	Structural foam	Betafoam™	89100/ 89124	2 component Pu	ambient	Increased crash performance, 400 g/cm³	validated
Paint shop, before wax	Structural foam	Betafoam™	89100/ 89112	2 component Pu	ambient	Increased crash performance, 200 g/cm³	available
Trim shop	Structural adhesive	Betamate™	2810	2 component Pu	ambient	Semi Structural, trunk lids, fast cure	
Trim shop	Structural adhesive	Betamate™	2850	2 component Pu	ambient	Semi Structural, roof, trunk lid, repair	
Trim shop	Structural adhesive	Betamate™	2850 S	2 component Pu	ambient	Semi Structural, roof, trunk lid, fast cure	
Trim shop	Structural adhesive	Betamate™	9050	2 component Pu	ambient	Structural, primerless on composites and paint, repair	
Trim shop	Structural adhesive	Betamate™	9050 S	2 component Pu	ambient	Structural, primerless on composites and paint, fast cure	

Table 4 Material overview (selection) of BETAMATE™ structural adhesives and BETAFOAM™ structural foams.



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