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Mixed Material Joining

Advancements and Challenges



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CAR's mission is to conduct independent research and analysis to educate, inform and advise stakeholders, policy makers, and the general public on critical issues facing the automotive industry, and the industry's impact on the U.S. economy and society.

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I. INTRODUCTION AND METHOD

The global emphasis on reducing carbon emission is pushing automakers to improve the fuel economy of their vehicle fleet. Vehicle performance (acceleration, road noise, vibrations, steering response, et cetera) and comfort features also needs to be improved every model year to meet customer expectations. Vehicle weight reduction, also called lightweighting, is being strategically pursued by automakers around the world to meet regulatory and market goals. Reduction of vehicle weight is mostly achieved through a combination of design optimization, downsizing, or down-gaging, and the use of lower-density materials with higher strength to weight and/or higher stiffness to weight ratios. New generations of automobiles are expected to contain an increasingly larger quantity and diversity of innovative material in their components. The leading lightweighting material candidates for vehicle body structures include advanced high strength steels (AHSS), aluminum, magnesium, and plastic and polymer composites. Innovative combinations of these materials are available in product forms such as sheet, plate, moldings/castings, and extrusions.

The use of these advanced materials creates the need to develop robust and cost-effective joining solutions for mixed-material parts and assemblies. Manufacturers apply expertise in a range of robust solutions well beyond conventional steel to steel resistance spot-welding (RSW), typically performed by assembly-line robots. Because new supply chains are developing, the use of newer lightweight materials in safety-critical automotive components often requires verification of their manufactured quality, including joint quality when they are integrated into a structure.

Design for joining is an iterative engineering process, which at a minimum, requires the consideration of diverse factors and properties of materials and joints such as energy absorption, fatigue, structural integrity, surface quality, formability and noise, vibration and harshness (NVH). In order to join advanced materials, a solid base of engineering knowledge and virtual tools for joint-modeling are required. Material selection and design involving these dissimilar materials drives the need to be able to factor chemical and thermodynamic interactions of adjacent components such as galvanic corrosion and thermal mismatch.

To improve vehicle manufacturers' confidence in multi-material joining, safety-critical parts are often inspected offline in time-consuming and often redundant operations using both destructive and non-destructive evaluation (NDE) methods. The successful application of mixed materials in future vehicles, therefore, should also consider life cycle aspects such as disassembly, repair and end-of-life processing of mixed material waste-streams. These multi-disciplinary challenges might best be addressed through collaboration and co-development involving the automakers and their multi-tier supply bases.

All steps of the vehicle design and manufacturing (and possibly across the product life cycle) should be considered in lightweighting decisions, as well as synergistic effects on powertrain and chassis accruing from reductions in weight of the body structure. To effectively incorporate different materials into the vehicle, the myriad of methods investigated to join them must be shown to be reliable, cost-effective and durable under varying loads and environments. This is one of the greatest challenges that the automotive industry faces with mixed materials.

Joining is a critical enabler to mixed material vehicles and represents different challenges relative to those with joining of monolithic materials - examples include; cost-effectiveness, thermal expansion, corrosion, durability, and process compatibility. Materials selection considerations are broad and can include considerations such as; energy absorption, structural integrity, stiffness for load transfer, surface quality, formability, NVH, life cycle and environmental factors, infrastructure, simulation, and many more.

This whitepaper investigates some of the popular methods for mixed material joining and identifies gaps and challenges and opportunities in their implementation for a mass-produced vehicle. The content of this whitepaper is the result of the information the CAR team collected by interviewing more than 20 joining experts at several vehicle manufacturers and high volume suppliers and conducting an extensive literature survey.

Our objective is to highlight challenges and opportunities in joining of dissimilar materials and to understand critical OEM requirements for mixed material structural joining and process capabilities and concerns. This paper will provide a reference document, which aims to clarify and recommend nomenclature, joint design strategies, joining methods, metrics, joint-isolation, testing, repair, and more to advance meaningful discussions and to identify opportunities for further research collaboration, and to accelerate knowledge transfer and access to additional lightweighting solutions.

II. MULTI-MATERIAL JOINING TECHNOLOGIES

A multi-material body structure utilizes different material combinations within a same part or assembly for optimizing weight and performance. The material combinations can include high strength steel with aluminum, aluminum with magnesium, metals with polymer composites, etc. Figure 1 illustrates the use of different materials in the same part to save weight while maintaining performance.

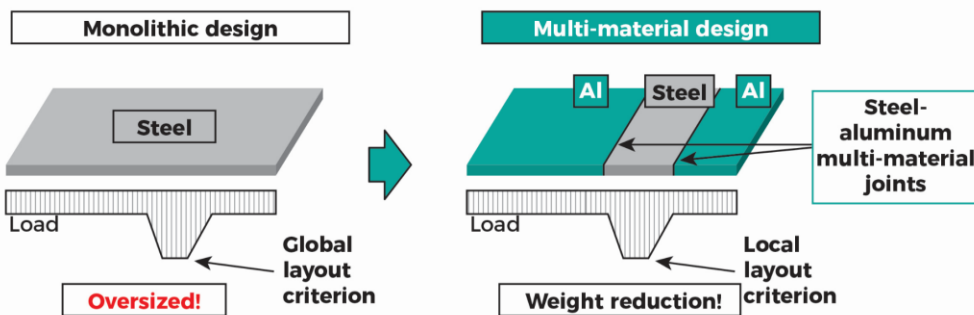


Figure 1: Example of a Multi-Material Design (Source: Fraunhofer Institute)

A large selection of mixed material joining technologies is already available and has been proven effective for a variety of applications. Although these technologies may not yet be ready for body shop applications where many production requirements must be met, further investment into research and development in these technologies may result in future high volume, industrial applications. Promising technologies for mixed material joining are highlighted in the following section.

Welding

- **Resistance Spot Welding**

Resistance Spot Welding (RSW) is a commonly used joining method for steels in the auto industry. Currently, the technology is being developed for dissimilar metals, particularly for welding steel to aluminum. General Motors claims that it utilized RSW for mixed material applications in 2012 when producing the 2013 Cadillac CTS-V. This application required joining steel to aluminum on the CTS-V hood at medium volume production levels. Figure 2 demonstrates the RSW process where sheet metal is forced between two copper electrodes at the spot of the weld which joins the dissimilar metals. This process of welding has been extensively tested and documented in engineering literature.

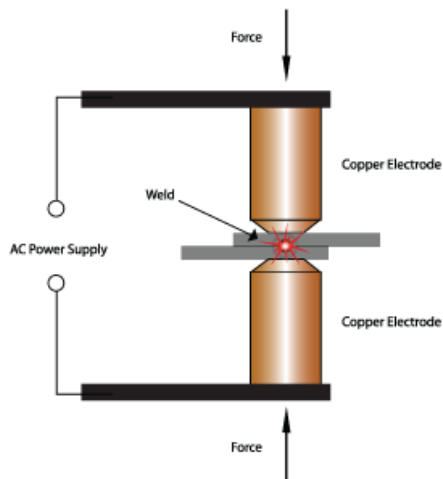


Figure 2: Resistance Spot Welding Process (Source: Vista Industrial Products, Inc.)

- **Friction Stir Spot Welding**

Friction Stir Spot Welding (FSSW) is also a widely-used technology for mixed material joining. It is a solid-state welding method. This process involves spinning a narrow tool tip positioned perpendicular to the stacked joining sheets at a speed between 2,000 and 4,500 revolutions per minute (rpm) depending on the application. When the rotating tool is forced into the sheet, friction heats the material to its plastic state without fully melting it. This process can be completed in less than two seconds. Figure 3 highlights the key aspects of an FSSW cycle.

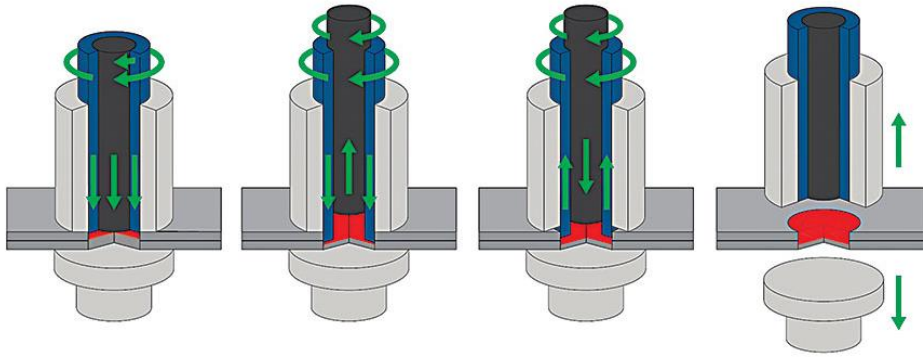


Figure 3: Friction Stir Spot Welding Process (Source: Coldwater Machine Co.)

- **Laser Brazing and Laser Welding**

Welding creates metal joints by applying concentrated heat at the joint to melt and fuse metals together. Brazing, on the other hand, involves significantly lower temperatures and does not entail the melting of base metals. Instead, a filler metal is melted and forced to flow into the joint through capillary action (Welding usually adds a filler material as well.) Laser brazing is typically used for sealing applications rather than applications requiring full mechanical strength from the weld. This process requires that the subject metals be orientated in a fillet weld, or a lap weld configuration which allows for a small gap between the materials which will be filled with brazing material. Figure 4 highlights this setup. Brazing material is melted into this gap using a laser. This laser heats the brazing material to its melting point but remains cool enough not to melt to subject metals. This process provides excellent corrosion resistance compared to other joining technologies.

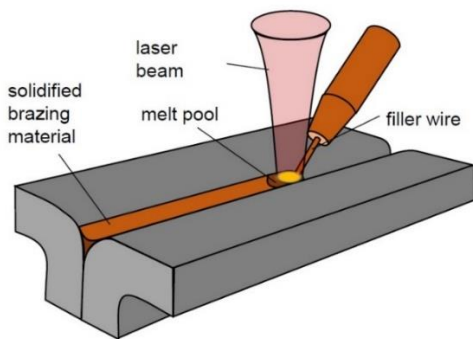


Figure 4: Laser Brazing Process (Source: ionix)

- *Spin Welding and Vibration Welding*

Spin welding and vibration welding are two friction welding processes commonly used for thermoplastics and polymer composites. The process of spin welding uses heat generated by rotational friction at the joint line to weld thermoplastic parts with rotationally symmetric joints (see figure 5a). Linear vibration welding physically moves one of two parts horizontally under pressure, creating heat through surface friction that melts and welds the parts together (see figure 5b).

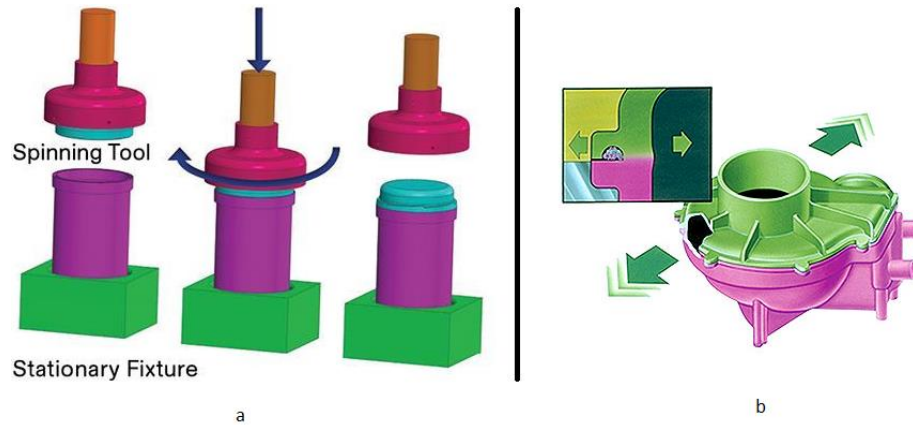


Figure 5: a) Spin Welding Process ; b) Vibration Welding Process (source: Branson Ultrasonics)

- *Infrared (IR) Welding*

Infrared welding is another joining process commonly used for plastic components with complex joining outlines. The surface layer of the component is melted by heat generated through infrared radiation. The components can then be joined by being pressed together (see figure 6). Infrared heat is transferred without contact.

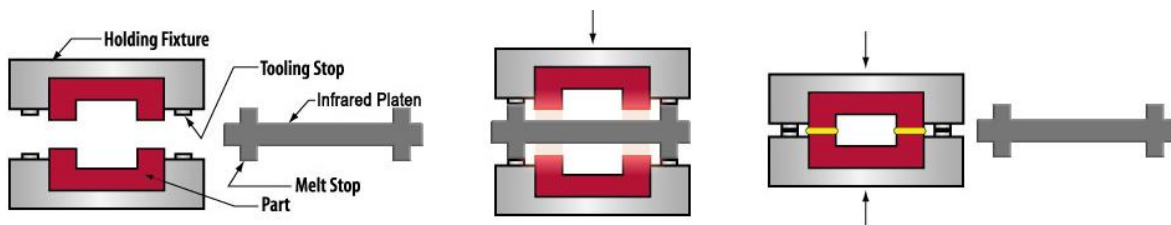


Figure 6: Infrared Welding Process (Source: Forward Technology)

Fasteners

- *Self-piercing Rivets*

Self-piercing rivets (SPR) are a widely-used technology which can be used in applications where corrosion is not a factor. This fastener works by being forced into a material stack and piercing the top layer material. The rivet then expands into the bottom layer and forces itself into a die. This process requires that the bottom layer material is somewhat ductile but in-turn produces a strong mechanical bond in under three seconds. Figure 7 shows the SPR joining process.

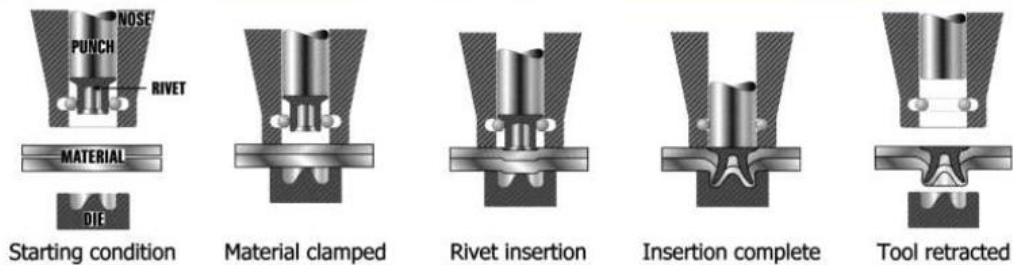


Figure 7: Self-Piercing Rivets Process (Source: Alcoa)

- *Clinching*

Clinching is a common joining technology that does not require consumables or pre-drilled holes. It is performed in a single step where stacked, ductile materials are pressed into a die with a punch. The punch forces the materials down and radially out into the die which creates a strong mechanical bond. This process does not provide corrosion resistance.

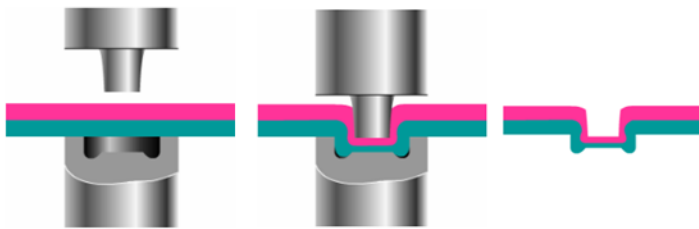


Figure 8: Clinching Process (Source: TOX)

- **One-sided High Speed Nails**

One-sided high speed nails are similar to SPR and clinching in that they do not require pre-drilled holes but differs in that it only requires one-sided accessibility to the joint. A specially designed tack equipped with a knurled point is forced into the stacked materials at a very high speed. This displaces the material and invokes a restoring force on the joint which joins the materials. This process requires that the subject materials have relatively high stiffness for sufficient restoring force.

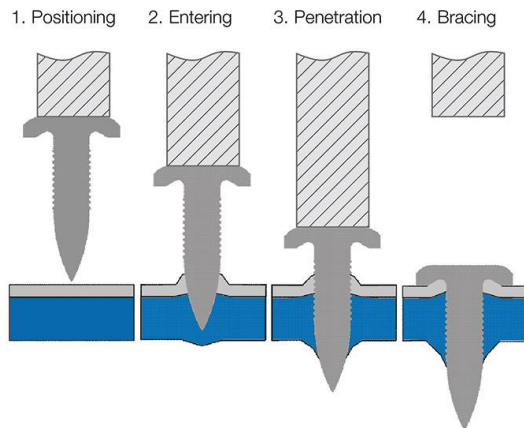


Figure 9: One-Sided High Speed Nails Process (Source: Böllhoff)

Adhesive Bonding

A vast selection of adhesives exists for very specific applications and requirements. This makes adhesive joining a strong candidate for particularly difficult material combinations such as metals to composites and polymers. Adhesives have a long list of advantages for mixed material applications such as their ability to join materials with dramatically different melting points while also sealing and separating dissimilar substrates, which in other cases would cause corrosion. Disadvantages of adhesive joining include their lack of standardization and testing methods and the requirement of surface preparation and long cure times for especially strong bonds. Figure 10 highlights the many mechanical property options of modern adhesives.

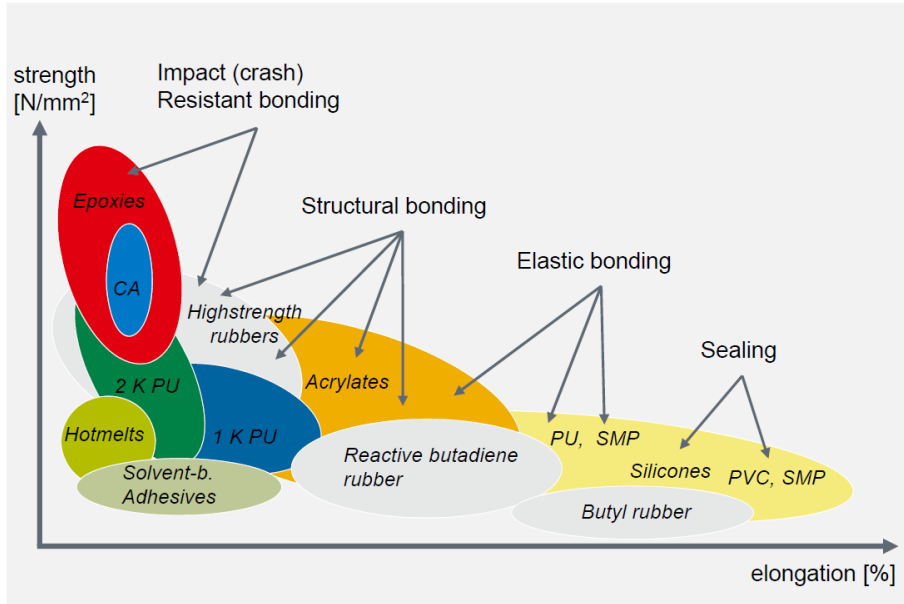


Figure 10: Property Range of Adhesives (Source: Henkel)

Magnetic Pulse Welding

Magnetic pulse welding (MPW) is the process of using a magnetic pulse to drive one material into another at extremely high speeds (upwards of 900 miles per hour). This action forms a bond at the molecular level by forcing atoms into each other at such a rate that the joining materials begin to share electrons. This process does not require heat and is typically performed on cylindrical joining applications such as the one seen in Figure 11.

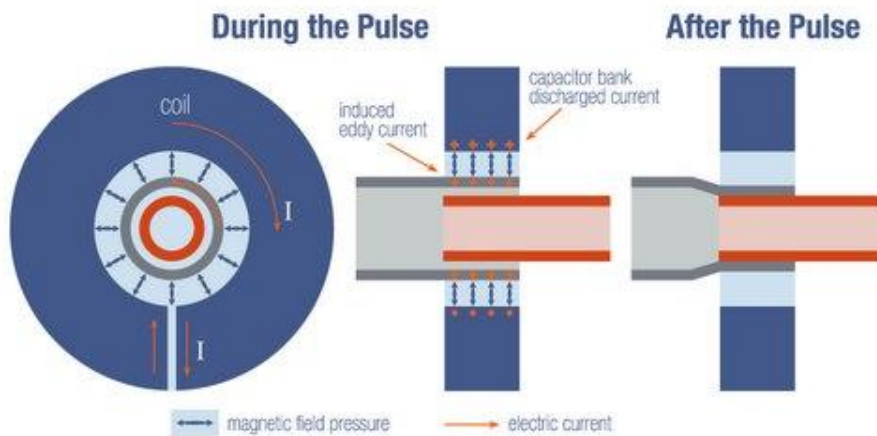


Figure 11: Magnetic Pulse Welding Process (Source: The Belgian Welding Institute)

Every joining technology may not work for all the assemblies. Figure 12 shows most commonly used joining technologies for different material combinations found in modern vehicles' body-structure. Adhesive bonding and fasteners are the only joining technologies that work for most of the material combinations including metal to composite joining.

Joining Technology/Material Combination	Steel-Steel	Steel- Al	Steel-Mag	Steel - Comp	Al-Al	Al - Mag	Al - Comp	Mag-Mag	Mag - Comp	Comp-Comp
Conventional Resistance Spot Welding	★	X*			X					
MIG/TIG Welding	X							★		
Friction Stir Spot Welding	X	X			X					
Laser Welding / Lazer Brazing	X	X			X			X		X
Fasteners (SPR, FDS, Nails)	X	★	X	★	★	★	★	X	X	X
Clinching	X	X	X		X	X				
Adhesive Bonding	X	★	★	★	★	★	★	X	X	★
Magnetic Pulse Welding	X	X			X	X				
Vibration Welding										X
Spin Welding										X
IR Welding										X

★ Most Common ; X Applicable

*GM patented process

Al = Aluminum, Mag = Magnesium, Comp = Polymer Composites, MIG = Metal Inert Gas Welding, TIG = Tungsten Inert Gas Welding

Figure 12: Joining Technologies Commonly used for Different Material Combinations

III. PARAMETERS CONSIDERED FOR SELECTING JOINING TECHNOLOGIES

To fully achieve the potential of lightweighting, vehicle manufacturers and suppliers need to integrate dissimilar materials and joining technologies into programmable assembly-line solutions such as resistance spot welding, laser welding, friction stir welding, weld bonding, self-piercing riveting, and a variety of fast-cure adhesive bonding processes to meet vehicle production speeds. There are several factors that an OEM considers before selecting a joining technology for its body shop; some of these factors are shown in Figure 13.

One sided/ Two sided	Multi Material Applicability	Technology Status	Piece Cost	Facility Cost / Requirements	Cycle Time
Inspection Method	Joint Strength	Corrosion	Ability to Model	Repairability	Ease of Use
Automated / Manual Process	Tooling Maintenance	Design Limitations	Throughput	Flange Width	Weight Savings
Change Flexibility	Ability to Join Hot Stamp Parts	Quality Control	Safety	Supply Chain	Joint Design

Figure 13: Parameters OEMs Consider for Selecting Joining Technologies for a Body Shop (Source: CAR Research)

A primary consideration is the maturity and applicability of the technology for the material combinations that need to be joined. Maturity of a technology is a subjective term which depends on the vehicle program. In broad terms, a mature technology can be used in a mass-produced vehicle (volume over 100,000 a year), has multiple product applications, and is available from multiple suppliers with a global base. Even if the technology is mature for high volume production and offers a better joining solution, it may be difficult to use due to design limitation.

An important consideration while selecting a joining process is the joint design. Figure 14 illustrates a few basic sheet metal joints. It is important to select the joining process according to the joint design and vice versa. For example, butt joints provide good lightweighting opportunity but they are not a good design alternative for adhesive bonding because in order to have good bonding strength, a large surface overlap area is needed between the materials. Lap joints are better for adhesive bonding; butt joints can be utilized if laser welding is used.

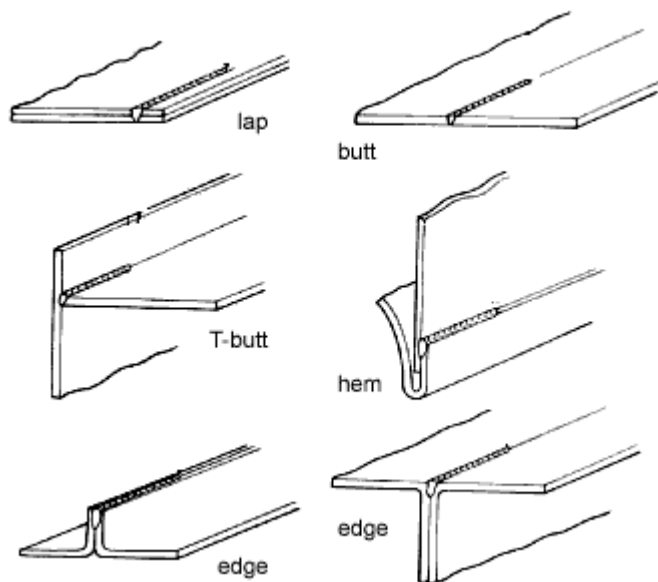


Figure 14: Basic Sheet Metal Joint Designs (Source: TWI)

Another important consideration is type of access available to the material surfaces. Some technologies such as resistance spot welding, riveting, clinching, et cetera can work only if there is two sided access available. If two sided access is not available, technologies such as laser welding, arc welding, one-sided nails, et cetera should be considered. Designers are demanding one-sided joining solutions to get more flexibility in part design.

Some joining technologies may also require special surface treatment. Adhesives work best if the material surface is cleaned prior to application. Recently, adhesive suppliers have launched products that can work with oily or uncleaned material surfaces. Type of surface coating may also alter the response of materials to various joining technologies. For example, galvanized steel is easier to weld than galvanized steel.

Other very important variables are cost and cycle time. Cycle time is the total time it takes for the two parts to go through the complete joining process. OEMs demand short cycle times, in some cases, under a minute for high volume vehicles.

In the modern, highly competitive automotive industry, quality control has become a central theme in technology and process selection as a result of consumers' demand for a high-quality product as well as increasingly strict federal vehicle safety standards to which OEMs must comply. There are hundreds of thousands of parts welded/joined every day in auto factories. Not all joints can be checked. OEMs look for technologies that can produce identical joints every single time. Resistance spot welding has gained the confidence of the industry for joining, due to its successful use over multiple decades.

Also, over the past few years, the regulatory pressure to improve fuel economy and performance is forcing automakers to introduce advanced lightweight materials such as high strength steels, aluminum, magnesium, plastics, and plastic and polymer composites faster than ever done before. OEMs are looking for weight reduction opportunities no matter how small. This trend is leading to selection of joining technologies which do not utilize any consumables and hence do not add weight. Clinching is a good example as the process does not involve additional elements such as screws, rivets or adhesives. Future vehicles are expected to have higher contents of advanced steels, aluminum, magnesium, and polymer composites. Joining solutions for various combinations of such high strength to weight materials are highly desired by the industry at the moment.

It is important to note that when joining two dissimilar materials, corrosion becomes a prime concern. Metals such as steel, aluminum, and magnesium have electro-potential differences due to their relative positions in the galvanic series. When such dissimilar material combinations are used in an environment susceptible to moisture, one of the materials corrodes faster than usual. Hence for dissimilar material combinations, a joining technology which can isolate the materials and help mitigate corrosion is preferred.

OEMs look for joining technologies that fit their current infrastructure and are easy to maintain. Basic types of machine-threaded fasteners such as bolts or screws require pre-drilled holes. This creates another step in the joining cycle which is not desired. Since most of the body shops in the North American region are now highly automated, it is preferred that the joining process is fully automated as well. The resistance spot welding process has achieved a high level of automation requiring almost no human intervention. Adhesive application can also be automated but certain issues like tip cleaning require human interaction in some cases.

Moreover, engineers need to match different joining approaches to optimize cost, cycle time, and joint quality. The key to achieve this is understanding and compensating for how material surfaces are prepared, transformed or distorted due to thermal loading/mismatch, sheet arrangement and, stack ups of various thicknesses. Establishing best practices and setting consistent standards or specifications for implementation and verification of each solution of materials combinations are pivotal in ensuring the expected performance of the multi-material assembly are met.

IV. TEST PROCEDURES FOR EVALUATING JOINTS

Testing is important in materials science and engineering to characterize and validate fundamental properties. The joint between dissimilar materials is commonly accompanied by mismatch in the mechanical, chemical and physical properties of the parts which have been joined. Mechanical requirements include the strength, toughness and stiffness of the joint. Chemical requirements include resistance to corrosion and degradation due to chemical attacks by the environment. Physical requirement for a joint may be limited to the need to seal an enclosure from the surroundings, and thus prevent access or egress of gas or liquid. It is important to understand the real-world loading conditions of the assembly before deciding on the type of test and loading conditions. It is also important to evaluate, not the joint, but rather a specific joining capability. Hence, many tests are made in order to evaluate the competence of the welder rather than the weld, while many adhesive joints are prepared to test the properties of the adhesives rather than the join (especially their shelf life or environmental sensitivity).¹ Testing is especially important for adhesives, where many variables are critical to the ultimate performance of the bonded joint.²

A joint can fail in multiple ways. Cracking is a common defect that occurs within welded joints. Typically cracking occurs because of the built-up stress that accumulates when a heated metal is rapidly cooled. In order to prevent this form of defect the metal should be annealed. Sometimes the issues aren't so much the joints themselves, but the surrounding area. Distortion of metal due to heat can cause undesired stress in the material. Oxidation is also a major issue with welded joints. An oxide can prevent a good weld from forming. Slag is another troublemaker when it comes to weld joints. This includes things such as dirt, debris, and oxides that are on the parts when welding occurs.³ Bonded joints can fail due to failure in adhesive to substrate adhesion, cohesion or both. Figure 15 illustrates modes of failure in bonded joints.

¹ Brandon, W. D. Kaplan, *Joining Processes, An Introduction*, ISBN: 978-0471964889

² Messler, Warren Savage, *Joining of Advanced Materials*, ISBN: 978-0750690089

³ Polymer Solutions, *Why do weld joints fail?*

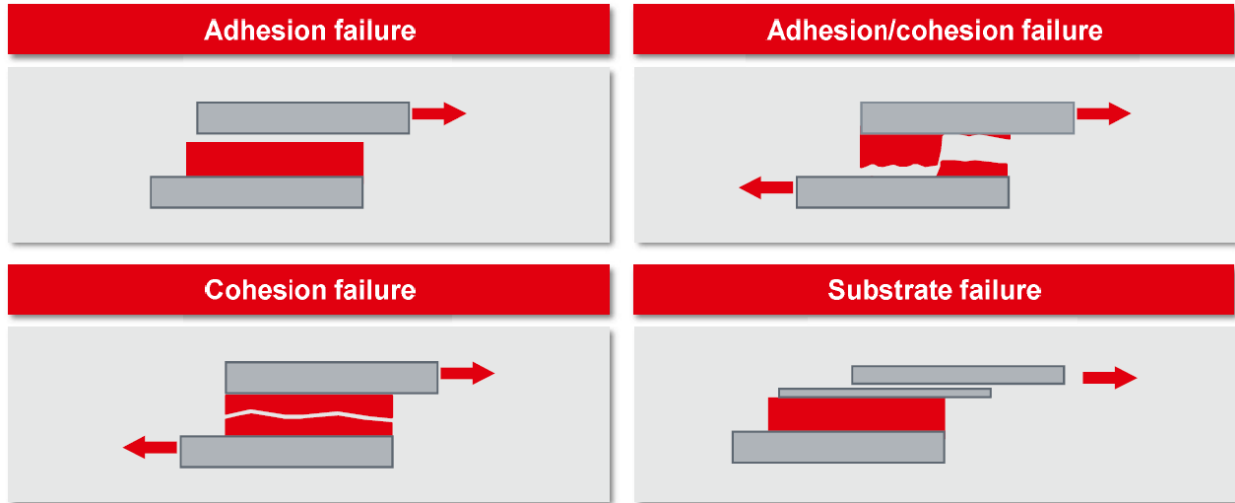


Figure 15: Failure Modes in Bonded Joints (Source: Henkel)

There are two kinds of tests that are often performed for checking the quality of joints:

1. *Destructive Test*: Some of these tests, such as tensile and bending tests, are destructive, in that the test specimens are loaded until they fail, so the desired information can be gained.
2. *Non-destructive Test (NDT)*: Other testing methods, such as the X-ray and hydrostatic tests, are nondestructive (NDT). This type of testing is also referred to as NDE or nondestructive examination and NDI or nondestructive inspection. The goal of these methods is to exam the welds without causing any damage.

Figure 16 illustrates some common adhesive testing methods. Similar testing methods are utilized for testing welded and mechanically fastened joints.

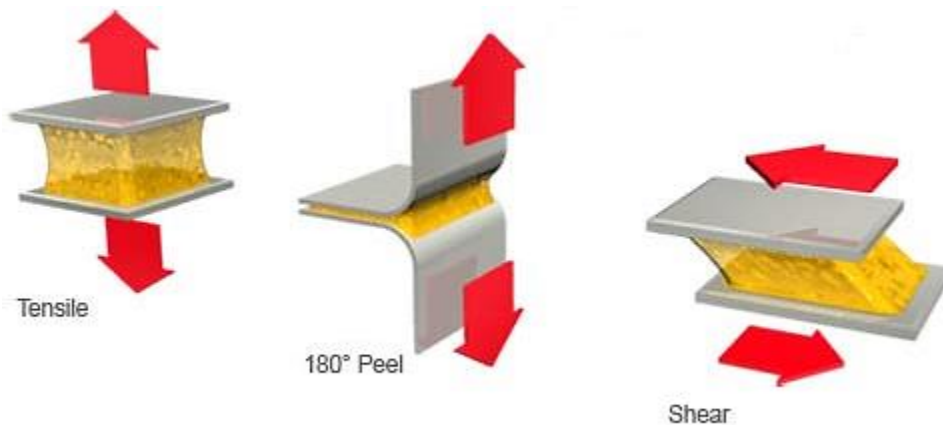


Figure 16: Common Adhesive Destructive Testing Methods (Source: www.adhesivetest.com)

V. MAJOR CHALLENGES WITH MIXED-MATERIAL JOINING TECHNOLOGIES

Materials selection criteria are aimed at satisfying engineering requirements by avoiding failure in both production and service. The implementation of a joining process must meet the engineering requirements for the system, both in the course of the joining process and throughout the subsequent service life of the assembled components. A joint between dissimilar materials is commonly accompanied by mismatch in the mechanical, physical and chemical properties of the components which have been joined.⁴ Described below are the major challenges with mixed-material joining as identified during the interviews with the subject matter experts at various OEMs and suppliers.

Corrosion

Corrosion is a natural process, which converts a refined metal to a more chemically-stable form, such as

“...major challenge is corrosion as we join two dissimilar and different electro-potential metals. Another challenge is how to make sure quality of joining is robust every time....” – OEM

oxide, hydroxide, or sulfide. It is the gradual destruction of materials (usually metals) by chemical and/or electrochemical reaction with the environment. Galvanic corrosion (also called bimetallic corrosion) is an electrochemical process in which one metal corrodes preferentially to another when both metals are in electrical contact, in the

presence of an electrolyte. When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes faster than it would by itself, while the other becomes the cathode and corrodes slower than it would alone. For a galvanic couple, the anode and cathode are determined by their relative position in the galvanic series (see Figure 17). For example, in the case of magnesium joined with steel, magnesium will act as an anode and will corrode faster. Galvanization (or galvanizing as it is most commonly called in the industry) is the process of applying a protective zinc coating to steel or iron to prevent rusting. Zinc serves as a sacrificial anode so that even if the coating is scratched, the exposed steel will still be protected by the remaining zinc.

⁴ Brandon, W. D. Kaplan, *Joining Processes, An Introduction*, ISBN: 978-0471964889

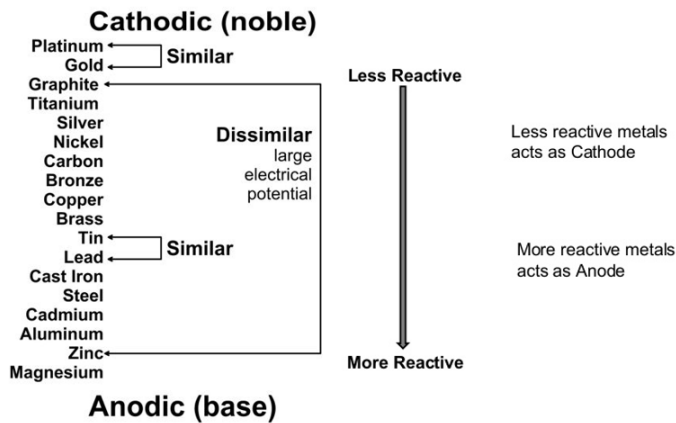


Figure 17: Galvanic Series

Previous CAR research ‘Assessing the Fleet-Wide Material Technology and Costs to Lightweight Vehicles’ concluded that most vehicle manufacturers are looking into mixed-material body structures to achieve mass reduction while maintaining cost targets and improving performance.⁵ As the industry responds to the global regulatory pressure to improve fuel economy, it will use more lightweight materials in the body structure. The four primary materials OEMs are experimenting with are steel, aluminum, magnesium and carbon-fiber composites. When joined together, due to the electro-potential differences, one of the materials will always corrode faster. The graphite present in carbon-fiber reinforced plastics (CFRP) is electro-positive to most of the materials used in the modern vehicles. Thus, CFRP when coupled with metals induce galvanic corrosion in the metal. Designers need to make efforts to isolate the joint between metal and CFRP.

In vehicle body applications where steel needs to be placed in contact with different metals including stainless steel, aluminum and copper, hot-dip galvanized or aluminized steel sheet structures is widely applied in a variety of environments to prevent corrosion. New developments in aluminum alloys and processing are making it possible to design parts with higher strength and energy absorption, and with wider manufacturing process windows while maintaining established corrosion resistance and surface quality attributes for finished part assemblies.

The challenges in application of magnesium, however, are more daunting in a mixed-material scenario. Because of its position in the galvanic series, magnesium is anodic to almost all other metals, and the galvanic corrosion of magnesium parts is difficult to mitigate by existing production methods. Hence, any method intended for joining magnesium in mixed-metal (or material) assemblies, must consider the fastener material selection, joint surface preparation, joint isolation and coating durability, in addition to the design of the joint strength for intended vehicle performance as well as cost-effectiveness of the overall solution. Currently, magnesium is mostly used in dry environments for components such as instrument panel beams, seat frames, lift gate inners, et cetera. Research is underway to develop robust and environmentally benign nano-ceramic coatings that have the required hardness and, the potential to isolate steel from magnesium, enabling them to be applied with steel fasteners. Successful

⁵ Baron, J., and Modi, S. Assessing the Fleet-wide Material Technology and Costs to Lightweight Vehicles. September, 2016, CAR.

demonstration of such coating technologies could enable the increased use of magnesium alloys to reduce vehicle weight and improve fuel economy.

Most of the OEM representatives interviewed agreed that understanding corrosion dynamics is very important. The technology used for joining such multi-materials assemblies should help in mitigating galvanic corrosion. Adhesives to some extent act as isolators between the two materials but fasteners are often used with the adhesives which results in contact between the materials if the fastener is not coated. Anti-corrosion coatings on fasteners, such as zinc, phosphate, polymers, et cetera act as a barrier to inhibit the contact between chemical compounds or corrosive materials. Overall, galvanic corrosion is a major challenge to overcome in order to use a mixed-material approach and the “right material at the right place” philosophy for vehicle weight and performance optimization.

Thermal Expansion

Thermal expansion is the tendency of matter to change in shape, area, and volume in response to a change in temperature. The coefficient of thermal expansion (CLTE) measures the fractional change in size per degree change in temperature at a constant pressure. Figure 18 shows how different materials react to thermal load. The body-in-white needs to go through the paint process which consists of a bake oven to cure the paint, sealants, and adhesives in the vehicle. The paint bake oven temperatures range from 180-250 degrees Celsius. The materials in a multi-material body will expand differently due to the difference in CLTE. This can distort the body-structure if the joints are rigid and do not allow for free expansion. For example, in a typical large plastic and metal assembly where movement is restricted, high compressive or tensile stresses can develop. Because in general the plastic part expands more, it develops a strain-induced compressive stress.⁶ An equal tensile stress develops in the metal part.

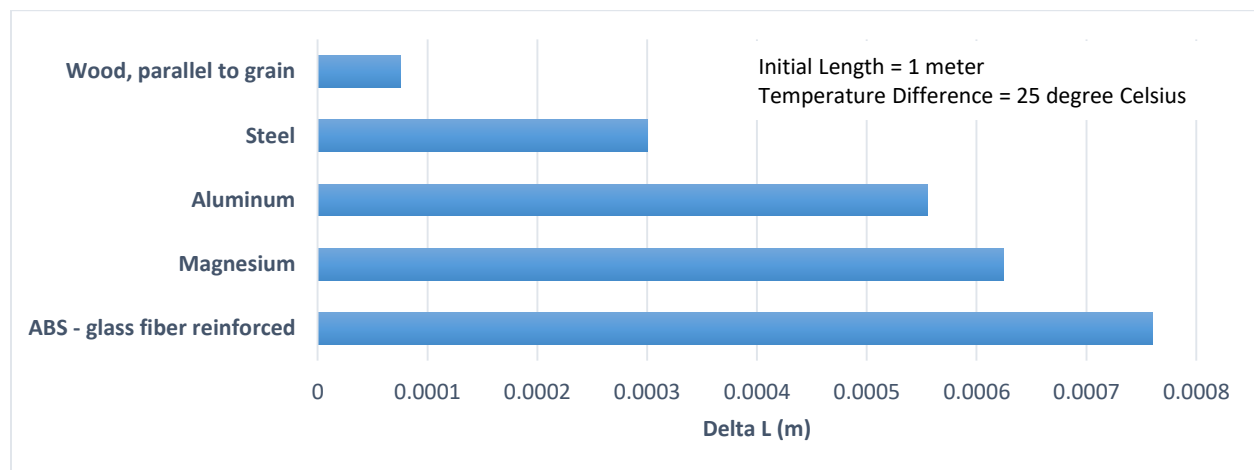


Figure 18: Different Materials Expand Differently Under Thermal Load (Source: CAR Research)

⁶ There are plastic materials developed which have lower than metal CLTE in one direction

Vehicle engineers are experimenting with various techniques to prevent distortion in mixed-material assemblies due to CLTE differences. Some of these issues can be mitigated by good design which allows free expansion without stressing the joint. Figure 19 shows an example of how design changes can help accommodate for thermal expansion differences.

“You can ask for good, fast, and cheap products, but you will always only get two of the three.” – Supplier

Flexible adhesives also accommodate some of the stresses while maintaining the joint strength, but these flexible adhesives might not have the properties required for joint performance. A major challenge for suppliers is to develop highly flexible, durable, and high modulus strength adhesives capable to be applied within the existing 60 second assembly process cycle and paint shop temperatures. Adhesive strength and flexibility have to be balanced.

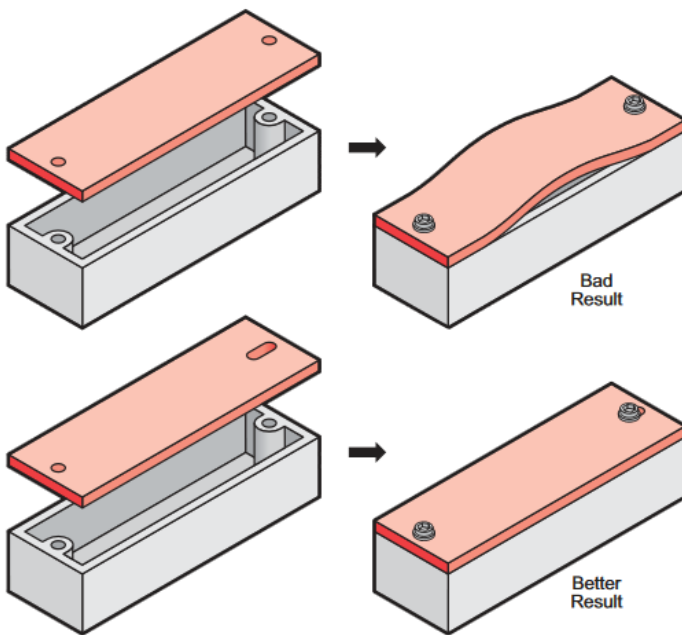


Figure 19: The Slotted Hole and Sliding Attachment at One End of the Plastic Cover in The Lower Assembly Enables it to Accommodate The Thermal Expansion Difference With The Metal Base (source: LANXESS Corporation, Joining Design Guide)

Cycle Time

Vehicle bodies are manufactured using predefined process flow where the time taken for each job is

“We need adhesives that can cure at room temperature at line speed.” – OEM

“You have to have the throughput. It should be under one a minute and survive the paint process.” – OEM

fixed. Usually for high volume production one body structure is made approximately every minute. To sustain this output, the cycle time (process time) for joining should be under a minute. Longer cycle times at one station slow the entire line of production, or a second station may have to be added. On the other hand, making one station super-efficient does not help either because it generates lag for other stations. Spot welding is often selected for joining sheet metal fabrications, stampings and assemblies because it is fast, reliable and economical. At present, welding robots can apply one resistance spot weld

(RSW) every second. Figure 20 describes a typical spot weld cycle. Spot welding of very dissimilar metals, such as aluminum and steel, is difficult because of different melting characteristics and conductivities. However, many companies are working to develop RSW for aluminum-steel combinations. Adhesive bonding is one of the technologies that is promising for multi-material applications, but adhesives can require curing time of 10-20 minutes depending upon the ambient temperature. Increasing the temperature reduces the cycle time but creates distortion in the material. Vehicle manufacturers demand adhesives which can cure at low temperature at production line rates.

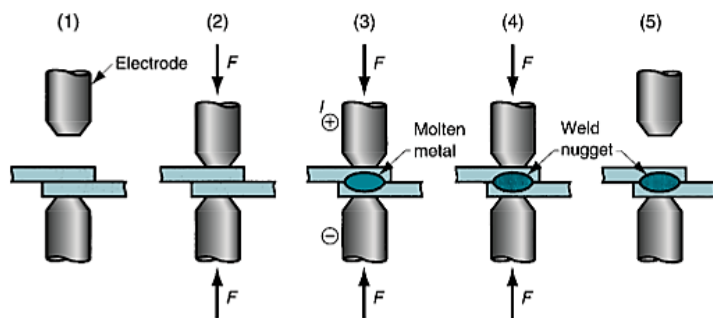


Figure 20: Stages in Making a Spot Weld (Source: Kullabs)

Standardization

A single car has about 30,000 parts, making it a very complex machine. Product designers strive to

*“There is a need to come up with a robust process like welding for mixed materials. **We need a dumb process that works for everything.**” – OEM*

simplify design and standardize components and manufacturing technologies as much as possible. The recent trend in the automotive industry is to reduce the number of platforms and promote more part sharing between vehicles to share engineering cost and reduce complexity. Among the various joining technologies, resistance spot welding is very standardized. The major OEMs follow the national or international standards for RSW. Also, spot welding works for

almost any type of steel combination with minor adjustments, which is a major advantage. On the other hand, adhesives and fasteners are the least standardized. Fasteners are custom made for the product application which increases engineering cost and complexity. Adhesives, too, are engineered as per the application and there are no available national or international standards. Adhesive suppliers do not want to commoditize their product because adhesive chemistry can be altered to better suit the application. OEMs however are not in favor of specialized products because it adds complexity in the body-shop. A product which can be purchased as a commodity from multiple suppliers is the priority as it reduces cost, distributes risk of supplier production failure and, simplifies the manufacturing process. OEMs also need the material and manufacturing technology to be available in all markets. At the moment, some of the material grades and joining technologies which are available in Europe are not available in North America. Also, the crash and emissions testing standards are different. Harmonization of standards will accelerate the pace of technology introduction and will help the industry in general.

Various performance tests need to be executed for qualifying the technology to be used in production.

“We invest time with design and manufacturing department at the OEMs. Then we need to deal with purchasing who always demands commodity products. Adhesives are highly engineered products; they will lose their performance if commoditized.” – Supplier

Most of the test procedures are decided by the OEMs. There are no standardized set of test procedures followed by the industry. This makes the qualification process time consuming and expensive. Also, the software companies are unable to create standard simulation packages

for joining analysis. Another issue with adhesives and fasteners is inventory management. The shelf life of adhesives is only a few months in a closed barrel. Once the barrel is open, it needs to be used quickly.

Nondestructive Evaluation and Computer Analytical Methods

While destructive physical testing is the best way to test joint performance, it is not economical for a

“Math models are important because if you don’t have predictive analysis, nobody is going to trust it before it is being used in the production for at least five years.” – Supplier

mass-produced vehicle. The automotive industry has been joining steels with steels and to some extent aluminum with aluminum over the last 100 years by using either welding or rivets. Nondestructive Evaluation (NDE) techniques such as ultrasonic, eddy current, X-ray, radiography, etc. have been developed to test welds. Computer-aided engineering (CAE) analysis tools are capable of predicting performance of welded assemblies. However, the results are not always accurate enough

to match real world performance. Vehicle designers often add extra welds for safety. Accurate prediction of real world performance, along with good process control is needed to eliminate unnecessary welds and reduce the safety factor.

The growing use of carbon and glass-fiber reinforced polymer composites poses significant challenges

“If the failure happens in the field but there are no mathematical models that can predict failure, you feel lucky, but you gain no confidence in the technology.” – Supplier

when these structures have to be attached to existing steel or aluminum/metallic vehicle sub-structures, such as frame rails, chassis, seating and roof structures.

Composites may be joined to metals with adhesives, which, in the manufacturing environment, are vulnerable to substrate contamination such as lubrication oil. The curing process, if not tightly controlled, can cause a number of process and downstream quality problems. Excess adhesives are known to contaminate the painting process if not applied or cured properly. Substrates intended for adhesive applications may have to be conditioned, driving up cost and process complexity. Joints with adhesives may be supplemented with fasteners or weld-bonded to overcome process variation or to increase peel strength. Due to these complexities, the tools and technologies for modeling of structural adhesive joints are not considered implementation-ready, when compared with tools for metal-to-metal joining. This forces the OEMs to perform destructive testing and to do extensive in-process control which is a roadblock for new joining technologies.

Intellectual Property

Most of the OEMs are putting forth efforts to solve their mixed-material joining problems. European

“Mixed-material bonding research is done at OEMs internal R&D centers. Hence the research resides at one OEM and nobody else can use it.” – Supplier

automakers in general are ahead of the curve in joining technology research and implementation. OEMs who have not used mixed-material body applications in the past and do not have big R&D centers struggle to maintain their competitiveness. Since the internal company research is often protected by intellectual property rights, other

companies cannot use it without paying a large premium. Likewise, individual universities and companies are also working internally to develop nondestructive evaluation methods. There is no consortium of companies in the North America region to study mixed-material bonding at a precompetitive level and publish results in a public domain format. There needs to be an industry-driven effort (primarily driven by the OEMs) to advance technologies for mixed-material joining.

Legacy Mindset

OEMs are very risk averse by nature. New technologies pose several risks such as part failure, supply-

“Fighting the old process is a major challenge.” – Supplier

chain delays, end-of-life recycling issues, high upfront cost, et cetera. The engineers want to take minimum risk because a small error can cost billions of dollars in vehicle recalls and legal fees. If a process or technology has been used for several decades and is proven in the field, the task of replacing it seems daunting. Even when the new joining technologies like adhesives are ready for mass production and meet performance and cost requirements, the OEMs are reluctant

“If you are doing the same thing for 20 years, you are most probably doing it wrong.” – Supplier

because lab testing cannot simulate all the conditions in the field. This legacy mindset is one of the biggest barriers to entry for any new technologies in the body shop. CAR’s previous research, ‘Material Qualification in the Automotive Industry’ identified leadership approval as one of the major barriers to entry for new materials.⁷ Regulatory pressure to improve fuel economy is pushing automakers to implement new technologies at a faster rate. OEMs are introducing these material and manufacturing technologies into premium low volume vehicles or in platforms which are not sold globally. For example, BMW used carbon fiber as the primary material for the i3 and used adhesives as the primary joining technology. BMW developed technology knowledge through implementation in the low volume vehicles such as i3 and i8 and then used the learnings in the 7-series which is produced in relatively higher volumes. Similarly, GM used 13 different materials and numerous joining technologies in the Cadillac CT6 which is a premium, low volume vehicle. Technology demonstrations in precompetitive collaborative research projects such as the Multi-Material Lightweight Vehicle (MMLV) (a concept

⁷ Modi, Shashank. Material Qualification in the Automotive Industry. Center for Automotive Research, Ann Arbor, MI. November 2016.

vehicle designed by Ford and Magna under a project funded by the U.S. Department of Energy's Vehicle Technologies Office) can help develop confidence in new material and manufacturing technologies.

Repair

Miles driven in the United States reached 3.148 trillion miles by the end of 2015, beating the previous

"The repair processes for new technologies need to work at dealership and independent repair facilities." – OEM

record of 3.003 trillion miles in 2007. For a sense of scale, 3.148 trillion miles is roughly the same distance as 337 round trips from Earth to Pluto.⁸ The increase in miles driven carries an unfortunate component.

Accident frequency is at its highest level in a decade, rising steeply in 2014 and 2015 in strong correlation with the spike in miles driven.⁹ Figure 21 shows that the frequency of vehicle collision damage claims rise with vehicle miles driven and has been continuously increasing since 2007. Thus, easy reparability is an important consideration while selecting materials and joining technologies. A difficult-to-repair vehicle will have increased insurance costs and this in turn may affect sales. The industry has learned how to repair steels joined with spot welding over a period of decades. New materials such as polymer composites, aluminum, and magnesium assembled together with the help of adhesives and fasteners pose a significant challenge for the repair personnel. Use of non-standard fasteners require custom tooling in the repair shops, which is an expensive investment for small shops. Recently, the industry has witnessed some breakthroughs in reversible bonding, enabling the auto repair industry, as well as advancements in weld tip design for direct resistance spot welding of aluminum and steel.

Some of the OEMs with composite intensive vehicles have flagship dealerships with trained staff. Customers are expected to remain loyal with the company's flagship dealerships for service and repair of their composite body-structure vehicles. OEMs also provide special training to dealership staff for aluminum body panel repairs.

⁸ U.S. Department of Transportation's (USDOT) Federal Highway Administration (FHWA)

⁹ Verisk Analytics, Inc.

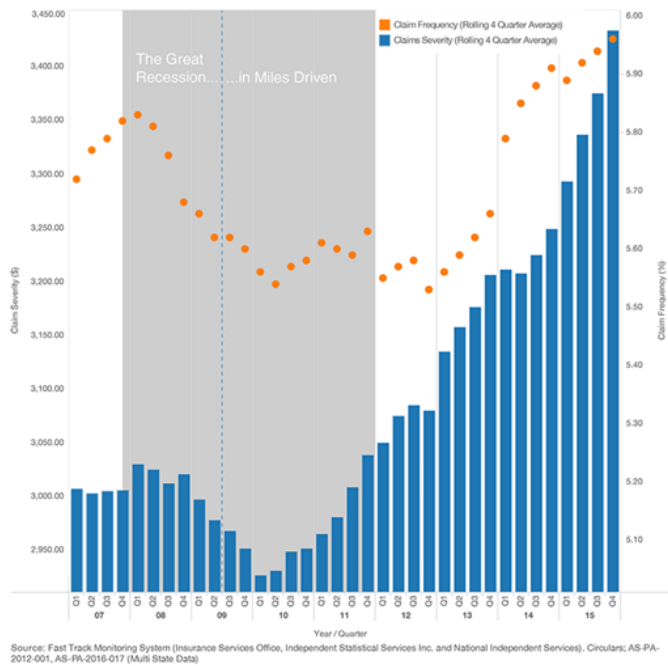


Figure 21: Frequency and Severity of Collision Physical Damage Claims from 2007-2015

Stranded Capital

The automotive industry is very capital intensive. Large investments are required to buy equipment and

“We are not building new plants very often. New body shops are an expensive investment. OEMs do not want to do that. If the platform is competitive then they will continue with it. Thus, integration of new technologies in existing plants is difficult.” – OEM

space for production. The body shop and paint shop absorb much of the money spent. The decision regarding which technologies to be used in future vehicle programs are made several years in advance of start of production. Once the component and assembly plants are up

and running, it becomes very difficult to change the manufacturing process or use a new technology because of the prior investments which run in billions of dollars. In North America, the body shops usually go through two changes in vehicle platforms before being fully amortized. This period can range from 12-15 years. OEMs are willing to put new equipment in the plant after the amortization cycle is completed to get the most value out of their investments. Due to the risk of stranded capital, that is, capital investment that becomes obsolete before full pay-back, OEMs are reluctant to implement new technologies into vehicles even if they are production ready and will improve vehicle performance.

Talent Gap

University education does not always line up with the skills needed for the real world, especially at the

“For the first time, we were able to hire a joining expert directly from a university. Most of the students coming out of colleges are just taught welding. This creates a talent gap.” – Supplier

undergraduate level. Welding has a well-established curriculum in most of the universities and community colleges, but it is very difficult to hire a joining (adhesives, fasteners etc.) engineer directly out of a

university. There is also a shortage of factory workers. Young students are not getting attracted towards manufacturing due to its “rust belt” image. Parents are not encouraging their kids to work for the automotive industry because they are fearful of another recession. CAR past research showed that one-third of motor vehicle & parts employees currently are or will soon be eligible to retire. Moreover, private and public spending on job training is not growing (hours of training per year remain flat). With the current scenario, the industry will face a dire shortage of talent in the near future. It is essential to change the image of the automotive industry and understand the needs and aspirations of young professionals. Young professionals today demand flexible working hours, clean environments, non-monotonous work, and competitive pay. Marketing on social media, factory tours, sponsored apprenticeships and internships programs, career fairs, et cetera may inspire young students to consider careers in automotive. One company or organization cannot possibly solve the talent crisis. It must be a collaborative effort between the automotive OEMs, suppliers, NGOs, and the government.

VI. FUTURE POTENTIAL WORK AND NEXT STEPS

Working through the multiple interviews of companies and meetings of engineers uncovered a list of items needing additional study. The list of issues continues to grow as new solutions are developed and tested. There are five of these issues listed here to be expanded on and reviewed as potential future work that may be undertaken by the Coalition for Automotive Lightweighting Materials (CALM). Every item noted here represents some level of value for the CALM companies and their customers. The list includes:

1. Determine which assembly plants are likely to refresh their body and / or paint shops next
2. Align fasteners with recommended adhesives
3. Publish the recommended testing procedures to use with particular material mixes
4. Outline the next steps for the existing CALM mixed-material lightweight door project¹⁰, to assign the joining techniques, locations, analysis, adhesives, fasteners and prototypes for the particular solutions studied
5. Determine and document alternative geometries to isolate, absorb or address thermal expansion

¹⁰ Stevens, M., Modi, S., & Chess, M., Mixed Material Solutions: Alternative Materials for Door Assemblies, CAR, August, 2016

All these ideas together help define the ultimate goal, to seek out alternatives of similar or less cost with any weight savings, regardless of the material used in the assembly.

Assembly Plant Change-over Forecast

It is apparent that there is a sweet spot in timing the recommendations for introducing new equipment, tooling and materials into an assembly operation. That specific point occurs as the plant is to go through its normal, planned upgrades, as it readies for change-over to manufacturing new model vehicles. This information is well known inside OEMs, and is part of their internal, regular program planning cadence. This information is almost never shared or published, as it represents key portions of a company's investment plans. Those specific dates typically could move several times over the 10- or 12- year plans for most body shop changes, and going public at an early stage would prove to be a distraction for the OEM as many project, location and model decisions change for a myriad of reasons.

The lack of this information drives the supplier community through unproductive pitches of ideas when there is little opportunity for application. For example, Ford recently completed the second round of product launches inside the F-150 plants as it introduced the Super Duty version. These plants now are on their second year of full production for the F series, and have yet to complete one model life cycle. Since most body shops use their installed infrastructure (robots mostly) for at least two product cycles (turns), it would be of little value to pitch new ideas to add new equipment or alternatives for these locations.

On the other hand, a plant that has successfully completed a full cycle of production on its original models launched when the body shop was first installed, and which is now at least half way through the four, five or six-year life planned for the most recent models launched, is ripe for considering new ideas, alternative equipment or layouts, and even new materials. As a plant enters its second half of the timing for the second turn, alternatives for the next major change are being analyzed and debated by the OEM. This is an important time for the supplier community to present their new ideas, as the OEM needs to incorporate these concepts before it locks in on a new plant layout supporting new or changed processes and materials. To support this concept, the CAR research team recommends:

Opportunity 1: Develop a database of all assembly plants in North America, noting their current products, date of launch, and expected timeframe for the next major change-over. This will provide a sequenced list of plants to the suppliers to consider for proposing new ideas and concepts.

Align Fasteners with Recommended Adhesives

Throughout the course of meetings and interviews with OEMs and suppliers, a common theme regarding fasteners was uncovered. While it was apparent that there will continue to be a demand for fasteners specified by OEMs, fasteners will be used in tandem with adhesives to enable multi-material solutions. It is also apparent there is no recommended listing of fasteners and adhesives published together, and the industry relies on the OEM to specify the required adhesive. The background of the engineers releasing the sub-assembly at the OEM are more directed to vehicle engineering, and less typically on the chemical engineering. It is of interest that the vehicle engineers may be the least able to determine the recommended link between specific fasteners and adhesives, without relying on the suppliers. This leads to the second of the five listed potential tasks to consider for CALM.

Opportunity 2: Publish a listing of cross-referenced fasteners and adhesives recommended by industry experts identifying the recommended combinations when dealing with multi-material solutions.

Publish Recommended Testing Procedures

Another discovery along the journey of many interviews was the wide variety of methods being applied across industry to validate the joints derived from combinations of fasteners and adhesives. Time and again during the meetings with various OEMs and suppliers, this lack of an accepted standard and / or method was noted as one of the leading roadblocks to multi-material solutions.

When an OEM specifies a steel solution, it relies on time-tested and proven analytic testing backed up by industry standard validation methods. For example, if a sub-assembly specified a typical steel to steel joint, a standard finite element analysis would be applied to determine the number and location of welds, and the resultant strength and durability of the joint to be expected. This would be backed up with a standard monitoring process of amperage in the welding process, and a standard pull and peel test in physical validation. These standards would be expected by any OEM and/or supplier, and are generic to the industry.

During the interviewing process, it was reported that the industry lacked such a standard process for the use of adhesives or combinations of adhesives and fasteners. In its place, the OEM or supplier typically measures the amount of adhesive applied, and then again after assembly to verify the process was correctly followed. While this validates a correct procedure was in place, it has no means to determine if the adhesive actually bonded.

There were some discussions indicating on-going research at the university level to provide an analytic approach to the design and simulated testing of bonded joints, but these were viewed as incomplete

Opportunity 3: Publish an industry-wide standard procedure for testing the bonding of various materials, and make this publication available to all universities conducting valuable research in this

and certainly not accepted as an industry standard at this point. This leads to the third proposed potential work for CALM.

Next Steps for CALM Door Project

Throughout the process of meetings and interviews there was much discussion about the dozen potential material combinations referenced in the original CALM mixed-material lightweight door project. The resulting presentation and white paper regarding door assemblies provided 12 alternatives of material combinations each resulting in a different total door weight. Each alternative represented a different targeted niche for application, with its own optimum volume and specific cost per pound saved as compared to the original mild steel design.

Several times during the interview process it was recommended to add these joining process recommendations to the existing CALM Door Study; this becomes the fourth of five proposed work efforts for the CALM coalition.

Opportunity 4: Document the variety of joining methods most appropriate for any of the 12 mixed-material door assembly solutions presented in the previous CALM study.

Recommended Geometries

At nearly every site visited, it was mentioned the OEMs or suppliers had issues with thermal expansion when applying solutions of mixed materials. This is due to the difference in expansion and contraction rates, as each material responds to temperature changes in its own unique manner. For example, an assembly of steel and aluminum has to accommodate for aluminum expanding at a faster rate than the steel when the vehicle goes through the heat of the electro-coating and paint bake oven processes. This also brings forth another issue, since as the assembly cools, the aluminum will cool faster than the steel.

As the interview process uncovered the issues, it also exposed the various methods deployed to remedy thermal growth at various rates. It became clear each OEM and supplier would work on altering the product geometry in order to address thermal expansion. A simplistic concept would be the addition of a bead in the design, to act as an isolator of the joint. What this feature looked like, how deep, how wide, where it started and stopped, etc., was figured out each time. There were examples discussed

Opportunity 5: Study, sort and document past remedies for thermal expansion differences in mixed-material assemblies. These would be published in a set of design guidelines for the overall industry, showing recommended geometry and material for the joints, including the recommended adhesives most appropriate for the particular application. This could be approached like the design-for-manufacturing guidelines typical in the automotive industry, where the guidelines are generic, and continuously updated.

where this was not discovered prior to tooling, which led to expensive rework just prior to launch activities. Therefore, the fifth recommendation of future work for the CALM coalition addresses this issue.

VII. SUMMARY AND THE WAY FORWARD

Regulatory pressure and customer requirements are pushing new lightweight materials into the vehicle body structure. The leading lightweighting material candidates for vehicle body structures include advanced high strength steels (AHSS), aluminum, magnesium, plastics and polymer composites. Vehicle designers are looking forward to apply the right material at the right place to achieve lightweight body-structures which are also optimized for better performance. Advancements in manufacturing technologies such as hot forming, resin transfer molding, 3D printing, etc. are making it possible to produce lightweight parts in high volume.

The auto industry faces a major challenge with joining dissimilar materials. A large selection of mixed material joining technologies are already available and have been proven effective for a variety of applications. The industry has witnessed recent breakthroughs in reversible bonding which will enable easy repair, as well as advancements in weld tip design for direct resistance spot welding of aluminum and steel. However, many promising technologies may not be ready for mass production and require further research and development efforts. The current major challenges include galvanic corrosion, thermal expansion differences in materials, longer production cycle times, non-availability of non-destructive testing methods for joint evaluation, and the risk averse nature of the OEMs. The automakers demand availability of technology across the globe. Also, the repair processes for new technologies need to work at dealership and independent repair facilities.

As the overall industry continues to push forward with lightweight mixed-material solutions, the Center for Automotive Research researchers expect to see additional breakthrough technologies, especially those related to: analytical nondestructive testing procedures, standardization of material, adhesives and fasteners across world markets, and flexible adhesives with lower cure temperature.

Joining is clearly a critical enabler to mixed material vehicles. This whitepaper investigates some of the popular methods for mixed material joining, and identifies gaps and challenges in their implementation for a mass-produced vehicle. This report highlights challenges and opportunities in joining of dissimilar materials and outlines critical OEM requirements for mixed material structural joining and process capabilities and related concerns. This paper serves as a reference document to help clarify and recommend nomenclature, joint design strategies, joining methods, metrics, joint-isolation, testing, repair, and more to advance meaningful discussions and to identify opportunities for further research collaboration, and seeks to help accelerate knowledge transfer and access to additional lightweighting solutions.

CAR and the Coalition for Automotive Lightweight Materials (CALM), a consortium of 40 major automotive suppliers, stand ready to take on the projects needed by the auto industry to attain these goals.