Evaluating Innovative Dissimilar Material Joining Technologies

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Acknowledgments

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

Because of the need to reduce overall vehicle mass, vehicle manufacturers are turning to a multi-material approach to vehicle construction more extensively than has been historically the case. However, because of the differences in the chemical and physical properties of these materials, joining is not as straightforward as, say, welding steel to steel.

This study, performed under the auspices of LIFT (https://lift.technology) and the U.S. Office of Naval Research (https://www.onr.navy.mil), looks at how various materials can be effectively joined as well as at various processes to perform the joining.

Introduction

Vehicle mass reduction or lightweighting has been an important tool for the automakers to achieve fuel economy, greenhouse gas emissions, and performance targets. Lightweighting can be best achieved by design optimization which involves the use of high strength-to-weight ratio materials, eliminating unnecessary material and design features by topology optimization, and the use of advanced manufacturing technologies (Baron & Modi, 2016). A famous phrase in the industry is “using the right material for the right application at the right cost to achieve the right performance.”

With the advent of Automated, Connected, Electrified, and Shared (ACES) technology, ligthweighting is expected to remain one of the top priorities in the automotive industry. Four major factors will contribute weight to future vehicles – 1) passenger comfort features, 2) batteries, 3) sensors and related components, 4) part redundancy for safety (Modi, Spulber, & Jin, 2018). The added weight needs to be compensated to improve fuel economy and performance (range for battery electric vehicles).

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. However, the joining of dissimilar materials is one of the major barriers in implementing the “right material for the right application” vehicle lightweighting strategy (Modi, Stevens, & Chess, Mixed Material Joining Advancements and Challenges, 2017).

Assembly Advances

For the better part of the 20th century, it was pretty much taken for granted that cars and trucks were made of steel. But in the early days of the industry, it was a mixed-materials approach to manufacture, including steel, wood, and fabric. For example, it wasn’t until 1912 that the Hupmobile and the Oakland vehicles featured all-steel bodies (Flink, 1990). The first mass-produced steel bodies and frames came out of the factory of the Dodge Brothers in 1915. This is not to say that vehicles like, say, the Model T didn’t use steel. But it was a matter of steel panels typically applied to a wooden frame. The innovation really came into its own in the 1923 Dodge, which had a closed sheet-steel body, and from that point on, there was the steel dominance that became characteristic of the industry.

Although there were certainly advances in metallurgy that made the use of the closed sheet design possible (e.g., it was necessary to have consistent material gauges), what really provided the impetus was the development of welding techniques by the Edward G. Budd Manufacturing company that facilitated this change.

The point is, assembling materials has long been important to the automotive industry. It is worth noting that the 1923 Dodge Model 30 had rivets in addition to welds to assure assembly integrity (Carey, 2019), and while mechanical fasteners were replaced by welding processes as steel became dominant, the fasteners have subsequently made a return.

Composites Emerge

But steel hasn't gone without significant material challenges. Arguably, the next big change in automotive materials occurred in 1953, when the first-generation Chevrolet Corvette was introduced. It was the first mass-produced vehicle to have an all-fiberglass body. The rationale deployed by the General Motors engineers was that because the fiberglass was lighter than steel of the time, the car had a better power-to-weight ratio (General Motors, 2012). In addition, the material provided greater design flexibility than could be achieved with stamped steel.

The initial Corvettes were hand-built. In 1954 production moved to St. Louis in 1954, then to a plant in Bowling Green, Kentucky in 1981. This is notable because with the exception of the Cadillac XLR—2003 to 2009—which both used composite components on a hydroformed structure the Bowling Green plant has been Corvette-only because of the manufacturing process is so different from any other vehicle in the GM portfolio.

Aluminum Advances

As time went on and due to regulatory challenges that necessitated things from more efficient powertrain to lighter-weight vehicles, another signal step in the auto industry occurred in 1994 when Audi launched an all-new flagship sedan, the A8, which featured what was known as the "Audi Space Frame," engineered to achieve mass reduction. It was the first mass-produced car featuring an all-aluminum monocoque structure. Joining techniques from riveting to bonding were deployed.

By the time of the fourth-generation Audi A8, which launched in 2017, the aluminum-only approach had given way to aluminum (cast nodes, extruded profiles, and sheets), steel (hot-stamped and gauge tailored), carbon fiber-reinforced polymer (CFRP; for the single largest component in the occupant cell, the rear panel), and magnesium (for the engine strut brace). Audi uses 14 different assembly processes to put this multi-material structure together (Audi, 2017). While the A8 is certainly a car that carries the margins that allow it to be produced with this array of materials, the fact on the ground today is that all vehicles are taking a multi-material approach.

Multi-Material Status Quo

When the 2015 Ford F-150 was announced to the public, the body was described as being made with "advanced, high-strength, military-grade aluminum," but the frame being "fully-boxed high-strength steel." The assembly of this pickup truck makes extensive use of rivets (self-piercing, in this case), adhesive bonding and welding (Ford, 2015). And according to Tadge Juechter, Executive Chief Engineer, Corvette, the 2020 Stingray, the eighth-generation Corvette, is a mosaic of materials, including, of course, composites (from glass fibers to carbon fibers) and aluminum base structure. As to the assembling of the various materials, he says that it is primarily adhesively bonded and mechanically fastened together. He says that while there is welding, it was minimized because of a concern with the heat's effect on dimensional accuracy (Autoline TV, 2019).

As there is a move to electric vehicles, there will be an increase in the requirement of reducing overall vehicle mass simply because vehicle manufacturers are interested in providing range, and the more mass that needs to be moved, the less range can be achieved. EV batteries are heavy and not likely to become much lighter in the near term. Hydrogen-powered vehicles are also heavier: a Toyota Mirai and a Toyota Camry are approximately the same size, yet the hydrogen-powered Mirai has a curb weight of 4,075 pounds, while the heaviest Camry is 3,572 pounds.

The point is, going forward, there will no longer be a single material dominant in vehicle construction. Each type of material has its own superior characteristics. If the vehicle is an Audi A8 or a Chevrolet Stingray, then the odds for the number of components being made of different materials is greater. But there is still the case of the Ford F-150 and its two primary materials, and the fact that the light truck is the single biggest selling vehicle in the U.S.

But there is a challenge that manufacturers face. When it was a case of a making a car or light truck with steel grades, the complexity was comparatively reduced as the materials were all ferrous. To be sure, there needed to be various weld schedules to accommodate the assembly of components, but there weren't issues like the galvanic corrosion that can occur when steel is connected with aluminum or the challenge of trying to securely attach a composite to a metal. Also, OEMs—even if they are producing A8s or Corvettes—must manufacture vehicles (1) at volume and (2) economically, so the processes used for assembly must be capable and robust. In addition to this, the assembly of vehicles must be done in a manner such that there are no structural failures that are the consequence of joining various materials. Structural integrity is paramount.

The Objective and Challenges

Many innovative joining technologies are developed by the suppliers but are not used by the automakers in production today because of the time-consuming qualification process. Technology qualification is a process that takes place between a material supplier and the customer (usually an automaker for tier-1 suppliers). The qualification process involves a series of iterative steps until the customer approves the supplier's technology for use in future products. The technology needs to pass various criteria set by the automakers, such as performance, initial investment, process cost, and supply-chain (Modi, 2016).

The Center for Automotive Research (CAR) and LIFT have worked with both process and materials suppliers to identify the joining technologies and the materials that could be potentially deployed in automotive assembly plants. The objective of this study is to look at the performance of various types of joining processes for mixed materials. The results of this study are published in the public domain and will be shared at multiple industry events, thereby increasing awareness and reducing the qualification barrier.

Companies and organizations participating are:

Table 1 lists are the materials selected for this study.

Table 1: Selected Materials

Type	**Material**	**Details**	**Gauge (mm)**
Aluminum	Aluminum 6022	T4 temper	0.8
	Aluminum 5754	O temper	2.5
	Aluminum 5182	O temper	1.5
	Aluminum Extruded 6082	T6 (lap shear), T4 (coach peel) temper	2.0
Magnesium	Magnesium AZ31B	Bare metal	1.1
Steel	Steel PHS 1500	Al/Si T1-47 coating	1.4
	Steel DP 980	GI 60G60G coating	1.0
	Steel Mild	Bare metal	1.0
	Steel Gen-3 980	GI 60G60G coating	1.5
	Steel Gen-3 1180	GI 50G50G coating	1.8
Polymer Composites	Glass Fiber Reinforced Plastic	Continuous, Nylon 6, ply thickness 0.25 mm, the layup is even number of 0/90 for each – 0/90/0/90/0/90/0/90	2.0

Note: The material suppliers provided uncoated materials. The joining suppliers performed surface treatment according to their respective joining technology requirements.

The joining processes tested are:

- Resistance spot riveting
- Element arc spot welding
- Refill friction stir spot welding
- Laser welding
- Friction element welding
- Adhesives
- Mechanical fasteners

The areas of the vehicle that are considered for the combinations of materials and the joining processes are:

- Roof structure
- Lift gate
- Shock tower
- B-pillar

The tests are both physical and virtual. The physical static tests were performed on material coupons that were joined with the selected joining technologies. There were both lap joints and coach-peel joints.[1] Coupons were prepared according to the SAE standards.[2] Physical tests were performed at LIFT, the industry-led, government-funded consortium in Detroit.[3]

Role of CAE

The project team found that the ability to simulate the joint performance in a computer environment is a critical parameter in the automaker's technology qualification process. Therefore, an engineering service provider (Detroit Engineering Products) was contracted to create computer simulation models of the tests and correlate computer-generated results with real-world results. The intent is to note the level of correlation that can be achieved and generate trust in simulation.

The joint performance was simulated using LsDyna-Explicit software. Then the results of the physical tests were compared to the results of digital modeling. For this report, the confidence interval for a positive correlation is 80 percent; that is, if the CAE results match with the real-world testing results at 80 percent or above, we mention it as a positive correlation.

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[1] For this project, impact peel and corrosion resistance were not evaluated. These tests will be performed in future research.

[2] SAE tests were done for all technologies except laser welded blanks (LWB). For LWB the following tests were used: 1) ASTM E8 Standard Test Method for Tension Testing 2) ASTM E643-15 for Ball Punch Deformation. Tension Test Coupons were prepared as per ASTM E8/E8M-09.

[3] Tests of laser welded blanks were performed at Shiloh Industries (Plymouth, MI) under the observation of CAR staff.

Several assumptions had to be made in order to simulate the joint performance. Detailed assumptions are captured in the CAE results of each test. Common assumptions include:

- Joints under study are sheet metal parts, aluminum extruded parts & glass fiber sheets. These joints are widely used in automotive body-in-white and their failure is more often observed in crash analysis than static events. To simulate the crash performance of these joints, LS-DYNA Explicit solver was chosen for FEA analysis.
- Material model (MAT_PIECEWISE_LINEAR_PLASTICITY) without strain rate is used for coupons. The failure of material coupons was predicted based on the induced plastic strains and thinning criteria.
- Static/Dynamic friction co-efficient of 0.2 is used for all contacting areas. An element size of 1.5mm is used for coupons/joints/adhesives. Coupons were modeled as 2d shell elements & adhesives/joints were modeled as solid elements.
- For adhesives, tied contact is assumed between the adhesive and materials. Therefore, only cohesive and mixed/thin-film failure can be simulated. A material model with damage criteria from suppliers is used for adhesives.
- Heat affected zone is not considered due to lack of information from the supplier.
- All material and joining technology data cards for simulation were provided by the respective suppliers.

The Joining Challenge

When two parts are mated together, an essential requirement is that the joint is as strong or stronger than the materials that are joined. In other words, the weld or the mechanical fastener shouldn't break or the adhesive shouldn't peel away from the material.

Several factors have to be considered, especially when mixed materials are involved. For example, when steel and aluminum are welded there can be a brittle intermetallic compound formed at the interface. When two materials have significantly different mechanical properties joined, there can be high-stress concentrations at the joint, which can lead to early failure. Because different materials have different thermal coefficients, this can set up a potential failure if the component is subjected to temperature fluctuations. And there is an issue of galvanic corrosion that can occur when two metallics like aluminum and steel are in direct contact. Each and all of these issues have to be taken into consideration for joining.

The Process Challenge

Although there have been advances in manufacturing equipment used in assembly plants, by and large, the fundamental design of body-in-white construction has been predicated on the use of resistance spot welding.

Resistance spot welding guns are structurally large clamps. Consequently, components have been designed so that there are openings that allow access of the arms to both sides of the component. Another consequence of the use of spot welding is that because the gun works like a clamp, fixturing is facilitated (i.e., the clamping action brings both pieces of material to be joined together). Generally, little preparation of the metal surfaces is required. Spot welding in body shops is extensively robotized. Because spot welds have been the status quo for joining, there is an extensive body of knowledge regarding the analysis of welds so that there can be confidence around weld performance.

All of these factors must be taken into account in using alternative processes. So among the considerations are:

- Is two-sided access required?
- Are pre-joining processes (e.g., hole drilling) necessary?
- What surface preparation is necessary?
- What are the fixturing requirements?
- Can the process be automated?
- Are manual operations required?
- Are post-joining operations required for the joint?
- What are the inspection requirements?

Material Combinations

The following material combinations were joined during the study:

1. Aluminum 6022 to Steel PHS 1500
2. Aluminum Extruded to Steel Gen-3 980
3. Aluminum 6022 to Magnesium AZ31B
4. Aluminum 5754 to Aluminum 5182
5. Glass Fiber Reinforced Plastic to Steel DP 980
6. Mild steel to Steel Gen-3 980
7. Steel PHS 1500 to Steel Gen-3 1180 GI

Material Preparation Methods

Industry partners are the sources for the materials used in the study (see Table 2). The materials suppliers either provided coupon-size samples or large sheets. In the case of sheets, they were cut into coupons at LIFT as per SAE standards. After the preparation of the coupons, they were sent to the joining suppliers in the study, who then used their processes to join the materials as specified. The number of joined test pieces for each of the materials combinations was sufficient to perform seven lap-shear and seven coach-peel studies at LIFT.

Table 2: Materials and their Supplier

Material Supplier	Material
Arconic	Aluminum 6022-T4, Aluminum 5182-O
Novelis	Aluminum 5754-O
Kaiser	Aluminum Extruded 6082-T6 (lap shear), T4 (coach peel)
Magna	Magnesium AZ31B Bare
BASF	Glass Fiber and Carbon Fiber Reinforced Plastic (Continuous Fiber, Nylon)
AK Steel	Steel PHS 1500 Al/Si, Steel Gen-3 1180 GI
US Steel	Steel DP 980 GI 60G60G , Steel Mild Bare, Steel Gen-3 980 GI 60G60G
Gestamp	Hot stamping of PHS

Note: Click on the material for more information.

The Processes

1. **Resistance Spot Riveting (RSR)™:** The process uses rivet made of steel or aluminum. The choice depends on the type of material that is the bottom sheet of the two to be joined. The top sheet has a hole in it. A feeder inserts a rivet into the hole, then a standard spot-welding gun is deployed to apply force and current to the fastener. The rivet is welded to the bottom material and there is a mechanical connection between the rivet and the top material. https://www.arconicrsr.com/

2. **Element Arc Spot Welding (EASW):** The process is a combination of a mechanical fastener, a rivet, and arc welding for combining aluminum and steel. The upper sheet is an aluminum alloy sheet, while the lower sheet is a steel sheet, in which the upper sheet is provided with a pre-hole. A hollow flanged steel rivet (element) is inserted into the pre-hole. Then, molten filler metal is deposited by arc welding in the hollow part of the element. That is, by performing arc spot welding from one side, the element, and lower steel sheet are firmly welded, while the upper aluminum sheet is tightly held between them. https://www.kobelco.co.jp/english

3. **EJOWELD® Friction Element Welding (EJOT):** This thermomechanical process uses a steel mechanical fastener. In joining a sheet of aluminum and steel, the fastener, through mechanical friction generated by rotation, penetrates the top aluminum sheet and then an axial force is used to complete the weld between it and the steel sheet. https://www.ejot.com/EJOWELD

4. **Refill Friction Stir Spot Welding (RFSSW):** Friction Welding, a type of solid-state joining, creates mechanical friction between workpieces in relative motion to one another, heating the materials until they reach a plastic state (non-melting) at the joint interface. The materials are then forged together by force, creating a joint. It offers numerous benefits over other joining techniques, including the elimination of filler metal or flux, higher quality joints, a minimal heat-affected area, and no coarse grain formation. https://www.coldwatermachine.com

5. **TEROSON® EP Structural Adhesives:** TEROSON EP 5065 is a solvent-free, two-component adhesive based on epoxy resins. It has high final strength both at high and low temperatures (-40°C-80°C). Curing occurs at both low and high temperatures. The cured adhesive film is hard, but not brittle. It can be used for both galvanized steel and aluminum. Teroson EP 5089, known as Terokal 5089, is a heat curing, solvent-free, metal to metal adhesive. It can be used on bare steel as well as zinc-coated surfaces, as well as aluminum alloys. It provides high shear strength and impact resistance. https://www.henkel-northamerica.com

6. **SikaPower® Structural Adhesives (Sika):** A one-component, epoxy based, bulk hybrid adhesives cured in electro-coat ovens. The adhesives are available with or without glass spheres, which help control the gaps between two joined materials. It can be used on steel, aluminum, CFRP and combinations of them. https://automotive.sika.com/en/solutions_products/body-shop-adhesives.html

7. **BETAMATE™ Structural Adhesives:** BETAMATE™ Flex 100F is a body shop adhesive with low modulus and high elongation that is ideal for minimizing residual strain and distortion to class A surfaces and which exhibits peel and impact resistance. BETAMATE™ 1640US is a toughened epoxy that is very robust in terms of multiple types of substrate/adhesion requirements. https://www.dupont/com/adhesives.html

8. **BlankLight® Laser Welded Blanks:** Laser welding of two or more aluminum grades into a single blank, resulting in additional strength where needed and reduced weight where possible. Laser welded blanks can help reduce mass and material, meet product design requirements and offer better formability. https://shiloh.com/solutions/blanklight/

Table 3 lists the joining technologies tested for each material combination.

Table 3: Selected Material Combinations and Joining Technologies

Material Combination	Joining Technology	Joining Supplier
Aluminum 6022 *to* Steel PHS 1500	Resistance Spot Riveting™	Arconic
	Element Arc Spot Welding	Kobelco
	EJOWELD Friction Element Welding	EJOT
	Refill Friction Stir Spot Welding	Coldwater
GFRP *to* Steel DP 980	TEROSON® EP 5065 Structural Adhesive	Henkel
	Hybrid Inserts	ARaymond
	SikaPower® -510 G MBX Adhesive	Sika
	BETAMATE™ Flex 100F Adhesive	Dupont
Steel Mild *to* Steel Gen-3 980	BETAMATE™ Flex 100F Adhesive	Dupont
	SikaPower® -550 G MBX Adhesive	Sika
	TEROSON® EP 5089 Structural Adhesive	Henkel
Aluminum 5754 *to* Aluminum 5182	Laser Joining of Blank	Shiloh
Aluminum 6022 to Magnesium AZ31B	Refill Friction Stir Spot Welding	Coldwater
	BETAMATE™ Flex 100F Adhesive	Dupont
	SikaPower® -510 G MBX Adhesive	Sika
	TEROSON® EP 5089 Structural Adhesive	Henkel
Aluminum Extruded 6082 to Steel Gen-3 980	Resistance Spot Riveting™	Arconic
	EJOWELD Friction Element Welding	EJOT
	Element Arc Spot Welding	Kobelco
Steel PHS 1500 to Steel Gen-3 1180	BETAMATE™ 1640US Adhesive	Dupont
	TEROSON® EP 5089 Structural Adhesive	Henkel
	SikaPower® -550 G MBX Adhesive	Sika

Note: ARaymond's Hybrid Insert joining technology was selected, but not included in testing due to lack of tooling to create the molded test plaques.

The Tests and the Results

For easy navigation, the test results can be accessed by clicking on the links below. The results can be viewed in two ways 1) by material combination and 2) by joining technology.

By Material Combination:

1. Aluminum 6022 to Steel PHS 1500 | VIEW RESULTS
2. Aluminum Extruded 6082 to Steel Gen-3 980 | VIEW RESULTS
3. Aluminum 6022 to Magnesium AZ31B | VIEW RESULTS
4. Aluminum 5754 to Aluminum 5182 | VIEW RESULTS
5. Glass Fiber Reinforced Plastic (PA6) to Steel DP 980 | VIEW RESULTS
6. Mild steel to Steel Gen-3 980 | VIEW RESULTS
7. Steel PHS 1500 to Steel Gen-3 1180 GI | VIEW RESULTS

By Joining Technology:

1. Resistance Spot Riveting (RSR)™ | VIEW RESULTS
2. Element Arc Spot Welding (EASW) | VIEW RESULTS
3. EJOWELD® Friction Element Welding | VIEW RESULTS
4. Refill Friction Stir Spot Welding (RFSSW) | VIEW RESULTS
5. TEROSON® EP Structural Adhesives | VIEW RESULTS
6. SikaPower® Structural Adhesives | VIEW RESULTS
7. BETAMATE™ Structural Adhesives | VIEW RESULTS
8. Laser Welded Blanks | VIEW RESULTS

Conclusion

Lightweighting has been an important tool for automakers to increase fuel economy, reduce greenhouse-gas emissions, and increase performance. With the advent of autonomous, connected, electrified, and shared (ACES) vehicles, lightweighting will become even more important since batteries, sensors, electronics, and comfort features add significant weight to the vehicles.

Automakers want to use the right material for the right application for design optimization to achieve their lightweighting target without sacrificing safety or performance. However, the joining of dissimilar materials is a major barrier to this strategy. CAR and LIFT independently studied various mixed-material joining technologies for various material combinations. Based on the studies performed here, the opportunities for mixed-material joining is something that is within reach of most OEMs. Although there is a significant installed base of equipment at OEMs and suppliers for traditional steel joining and a growing amount of aluminum joining, as shown in this study, equipment suppliers have developed processes and equipment that facilitate the joining of different types of materials to one another.

It should be noted that with well over 100 years' experience with single material joining—experience that has given rise to highly efficient equipment for joining and quality assessment—there will need to be more work done to create a compelling case for alternative joining processes in automotive.

Future Research

Although an array of materials and processes were studied here, future research should be performed on a wider array of material types and gauges. Given the variety of vehicle types that are characteristic of the auto industry, there are different use demands, such as the difference between a subcompact car and a heavy-duty pickup. This means that the vehicles are engineered with different types and gauges of materials, well beyond the scope of the elements considered herein.

Another area where there needs to be more research done is in the area of the ability of the processes to operate at automotive line speeds. Resistance spot welding has had several decades of use in automotive factories the world over and consequently has had years of improvement made.
To provide an alternative, there must be a level of confidence in the capabilities and reliabilities of the new joining processes. Future research also needs to performed on other factors in technology qualification such as initial investment, supply-chain availability, after-sales service, and cost. Also, additional research is needed for testing other joining requirements, such as corrosion prevention and fatigue.

APPENDIX

Literature Survey

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The vehicle body and chassis structures are now being built using multiple materials that include low carbon steels, advanced high strength steels, aluminum and magnesium alloys, and glass and carbon fiber composites. In a multi-material structure, joining considerations between materials with diverse material characteristics become a critical material selection and joint design issue. Joint performance in multi-material designs of automotive structures depends on the following factors.

1. **Material combination**: The material combination is important to consider since the joint performance, defects in the joined area, and overall joinability depend on whether the materials being joined are either metallurgically or chemically compatible. An example will be steel and aluminum for which any liquid-phase welding, such as spot welding, will create a weak joint due to the formation of brittle intermetallic compounds at their interface.
2. **Joint design and material thicknesses**: Joint design and material thicknesses not only determine the stiffness of the structure, but also the stresses that are induced at the joint due to applied loads between them. If there are large differences in the mechanical properties of the materials being joined, the stress concentrations at the interface between them can cause early failure.
3. **Thermal expansion or contraction mismatch**: Large differences in the coefficients of thermal expansion or contraction of joined materials can induce thermal stresses when there are significant temperature changes during the joining process and during service. If the thermal stresses are tensile in nature, there may be early failure of the joint. A thermal mismatch can also distort the joined part.
4. **Potential for galvanic corrosion during service**: Galvanic corrosion occurs due to the differences in electrode potentials of dissimilar materials in contact with each other in the presence of an electrolyte, which for example, can be only water. An example will be steel and aluminum.
5. **Fixture design requirements and constraints during the joining process**: Fixtures and constraints are required to create the proper clearance between the materials being joined and reduce the deformation due to thermal mismatch or mechanical forces.

Industry Need for New Joining Technologies

The industry need for joints is that they must be robust with high joint strength and as little variation as possible, operationally fast, reliable, relatively low cost, easy to apply, and safe to the operator. To adopt a new joining technology in an automotive assembly plant, investments in new equipment, skilled workforce development, and equipment maintenance are also important considerations.

Ideally, the joint strength should be such that joint failure does not occur before the substrate failure. This requires not only high static strength but also a high fatigue strength if the joint is subjected to fatigue cycling. Also, a high impact strength if the joint is subjected to impact loading. It is also important that the joint strength does not reduce over time due to corrosion, stress relaxation, torque loss, and environmental degradation.

For a joining technology to be successful in an automotive assembly operation, it must be fast and reliable. For this, cycle time is an essential factor. Additionally, the following issues are also important.

(1) Does the joining method require access to both sides of the assembly?
(2) Does the joining method require any pre-joining operation (for example, pre-drilling holes)?
(3) Does the joining method require surface preparation and/or corrosion protection?
(4) Does the joining method require special tools, fixtures, or additional material?
(5) Can the joining method be easily automated?
(6) Does the joining method require a significant manual operation?
(7) Can the joint be inspected quickly and easily?
(8) Does the joining method require any post-joining operation?

The cost of joining also plays a role in deciding the acceptability of joining technology. The cost may include pre-joining and post-joining operations cost, material cost and investment cost.

Current Joining Methods and their Applications

There are several established joining methods in the automotive industry. In addition, a number of new joining methods have evolved due to the need to join dissimilar materials. These joining methods can be classified into the following categories, namely

(1) Liquid phase joining
(2) Solid-phase joining
(3) Mechanical joining
(4) Threaded fastening
(5) Adhesive bonding
(6) Mixed or hybrid joining
(7) Other methods

Joining techniques in each category and the material combinations for their use are listed in Table 4. Among these joining methods, resistance spot welding (RSW), laser welding (LW), self-piercing riveting (SPR) and clinching (CL) are already used in automotive assembly operations of the body, chassis and frame structures. Friction stir welding (FSW) and other solid-phase welding processes are now well-developed, but their use in automotive assemblies is limited.

Table 4: Popular joining methods for automotive applications
S; Steel, A: Aluminum, M: Magnesium, C: Composite, P: Plastic, All: All Materials

Type	Joining Method	Abbreviation	Material Combinations
Liquid Phase Welding	Resistance Spot Welding	RSW	S-S, A-A, S-A
	Laser Welding	LW	S-S, A-A, S-A
	Gas Metal Arc Welding	GMAW	S-S, A-A
	Tungsten Insert Gas Welding	TIG	S-S, A-A
	Electron Beam Welding	EBW	S-S, A-A
	Magnetic Pulse Welding	MPW	S-S, S-A, A-A, A-M
	Resistance Element Welding	REW	S-A
	Element Arc Spot Welding	EASW	S-S, A-A, S-A
Solid-State Welding	Friction Stir Welding	FSW	S-S, A-A, S-A
	Friction Stir Spot Welding	FSSW	A-A, S-A
	Friction Welding	FW	A-A, S-A
	Ultrasonic Welding	UW	A-A, S-A
	Friction Element Welding	FEW	A-A, S-A
Mechanical Joining	Self-Piercing Riveting	SPR	A-A, S-A, M-M
	Clinching	CLN	A-A
	Blind Riveting	BR	S-S, A-A, S-A
	Flow Drilling	FD	S-S, A-A, S-A
	Punch Nailing	PN	S-S, A-A, S-A
Threaded Fastening	Bolts and Nuts	B & N	All
	Metal Screws	MS	All
Adhesive Bonding	Adhesive Bonding-Epoxy	AB-E	All
	Adhesive Bonding-Polyurethane	AB-PU	All
	Adhesive Bonding-Acrylic	AB-A	All
Mixed or Hybrid Joining	Weld Bonding	W-B	S-S, S-A, A-A
	Rivet Bonding	R-B	S-S, A-A, S-A
	Clinch Bonding	C-B	S-S, A-A, S-A
Other Methods	Laser Brazing	LB	A-A, S-A
	Insert Molding	IM	C-C, C-S, C-A
	Hemming	HM	S-S, A-A, S-A
	Clipping	CL	All
	Snap Fitting	SF	P-P, P-S, P-A

Source: CAR Research

RSW is the principal joining method for low carbon steel body construction, and its practice is well established. RSW is also used with advanced high strength steels; however, the welding parameters are somewhat different from those used for low carbon steels. The use of RSW for joining aluminum alloys also needs adjustment in welding parameters because of the differences in material characteristics, such as electrical resistivity, thermal conductivity, and melting point. Joining aluminum to steel is problematic due to the large difference in their melting temperatures and the formation of brittle intermetallic compounds at the interface between them. Like RSW, LW is also a liquid phase welding process. It is used mainly in the manufacturing of tailor- welded blanks in steels and aluminum alloys, but its use for joining aluminum with steel is also problematic for the same reasons as in RSW. SPR and CL are mechanical joining methods and are used mainly for joining aluminum alloys. They are combined with an adhesive to make the joints stronger. SPR provides higher joint strength than CL and has been used in aluminum-intensive vehicles more extensively than CL and RSW. SPR can also be applied to join steel with aluminum provided proper corrosion protection measures are taken.

Adhesive bonding, either by itself or in combination with spot welding, riveting and clinching, is becoming a more common joining method for dissimilar materials. There are now many high-strength epoxies, urethane, and acrylic adhesives in the market and many of them provide high crash energy absorption. There are several advantages of adhesive bonding; the key among them is that it is a continuous joint and it increases the stiffness of the joined parts. Another of its benefits is that since the adhesive layer isolates the joined materials, it reduces the possibility of galvanic corrosion between them. Requirements for a good adhesive joint:

- Adhesion: Adhesive failure mode should be 100% cohesive failure (when cohesive failure is required). In some cases, substrate failure may be acceptable.
- Strength: Specified quasi-static strength requirements must be met before and after environmental exposure(s).
- Durability: Adhesive bond must be durable over the lifecycle of the joint i.e., environmental resistance & fatigue durability.

A number of joining methods have evolved in the last few years that are finding greater use in joining dissimilar materials, especially steel and aluminum. They are flow drilling (FD), punch nailing (PN), resistance spot riveting (RSR), resistance element welding (REW), element arc spot welding (EASW) and friction element welding (FEW). Both FD and PN are mechanical joining methods and relatively high-speed operations. In FD, a threaded screw, called the flow drill screw (FDS), is drilled into the material stack using a rotary drive, whereas in PN, a serrated nail is punched into the material stack using a pneumatic axial force. In RSR, REW, EASW and FEW processes, a third element (for example, a rivet) is introduced between the materials to be joined. The joining occurs between the third element and the bottom sheet by riveting, spot welding, arc welding or friction welding. For example, in the RSR process, two or more sheets are placed between the electrodes of a standard spot welding gun. The upper sheet has pre-drilled holes for the rivet, while the bottom sheet does not contain any hole. At the beginning of the joining cycle, a rivet is placed under the top electrode that applies an axial force on the rivet and passes electric current to the rivet and the bottom sheet to form a weld between them. The top sheet is not welded to the rivet and is thus simply joined to the bottom sheet through the rivet. Typical cycle time is 3 to 5 seconds, which is comparable to the resistance spot welding process. For the RSR process, the bottom sheet has to be electrically conductive so that it can be welded to the rivet.

Test Methods for Qualifying and Commercializing the Technology

There are several ASTM, SAE, and ISO standard test methods for determining strengths of spot welded and adhesively bonded joints. A list of these standards is given in Tables 5 and 6. A survey of the ASTM and SAE standards showed that many of these standards are similar. The three most common tests conducted in industry and academic studies to qualify spot-welded joints are the lap shear test for shear strength, T-peel test for peel strength and cross-tension test for tensile strength of spot-welded joints. For adhesively bonded joints, lap shear and T-peel tests are used. The cross-tension test is not applicable to adhesive joints and there are no standards for cross-tension tests for adhesives.

Table 5: Standard test methods for spot-welded joints

Standard	Title
ISO 14270:2016	Resistance welding – Destructive testing of welds – Specimen dimensions and procedure for mechanized peel testing resistance spot, seam and embossed projection welds
ISO 14272:2016	Resistance welding – Destructive testing of welds – Specimen dimensions and procedure for cross tension testing resistance spot, seam and embossed projection welds
ISO 14273:2016	Resistance welding – Destructive testing of welds – Specimen dimensions and procedure for tensile testing resistance spot, seam and embossed projection welds
ISO 10447:2015	Resistance welding – Testing of welds – Peel and chisel testing of resistance spot and projection welds
AWS D8.9M:2012	Test methods for evaluating the resistance spot welding behavior of automotive sheet steel materials

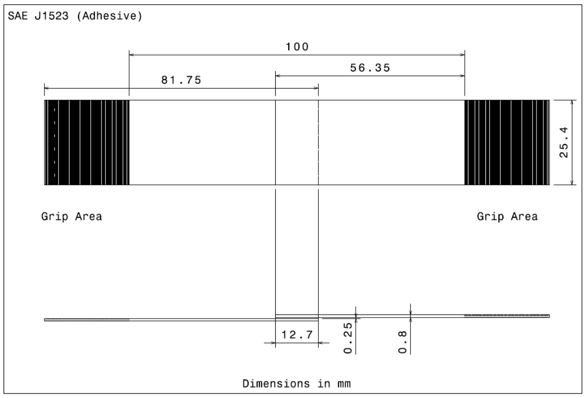
Table 6: Standard test methods for adhesively bonded joints

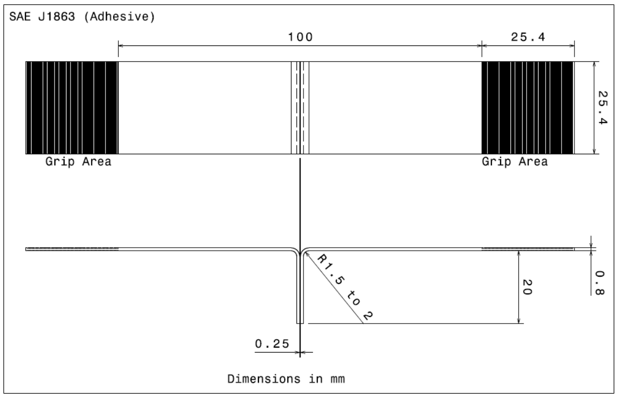
Standard	Title
ASTM D1002	Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal).
ASTM D1876	Standard Test Method for Peel Resistance of Adhesives (T-Peel Test).
ISO 4587:2003	Adhesives -- Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies
ISO 11339:2010	Adhesives -- T-peel test for flexible-to-flexible bonded assemblies
SAE J1553_199504	Cross Peel Test for Automotive Type Adhesives for Fiber-Reinforced Plastic (FRP) Bonding
SAE J1525_201706	Lap Shear Test for Automotive -Type Adhesives for Fiber Reinforced Plastic (FRP) Bonding
SAE J1523_201202	Metal to Metal Overlap Shear Strength Test for Automotive Type Adhesives
SAE J1863_201202	Coach joint fracture test

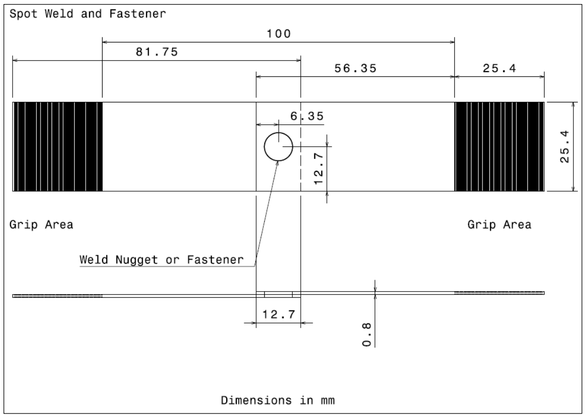
After reviewing the various ASTM and SAE standard test methods and published articles on joint testing and evaluation, the following two tests are recommended for qualifying the joining technologies. Specimens recommended for both tests are shown in in the pictures below.

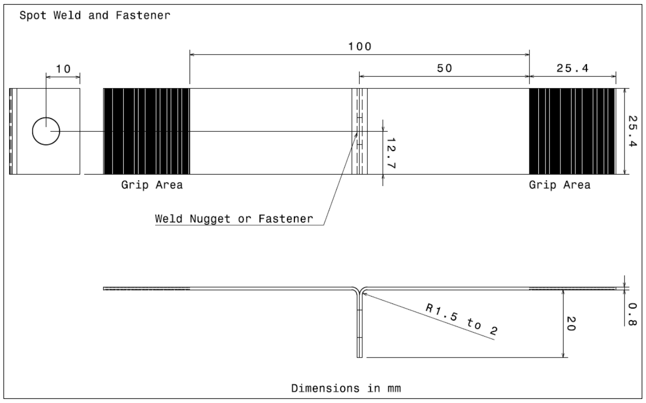
1. Lap shear test – SAE J1523
2. Coach peel test – SAE J1863

Both tests were conducted at a crosshead speed of 10-13 mm/min and room temperature. At least five specimens should be tested for each joint combination. The load-displacement diagram should be recorded and the peak load value should be noted for each test. The average peak load, range and standard deviation should be reported. Typical load-displacement diagrams and the failure modes should also be reported.





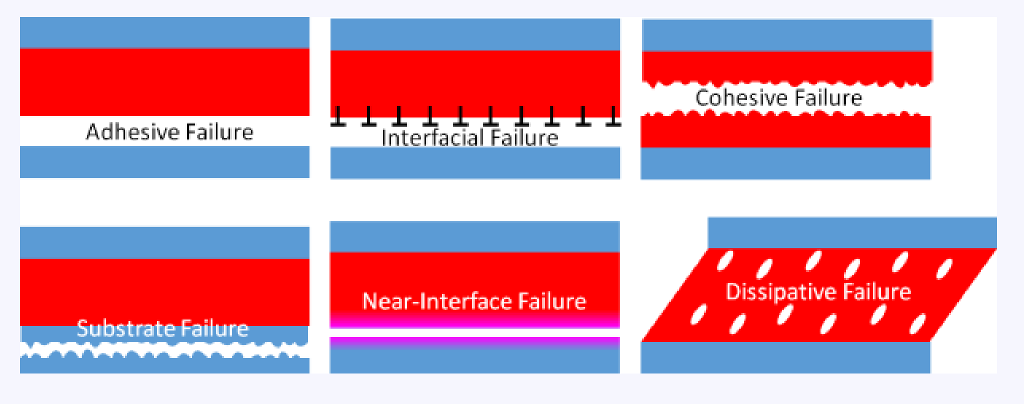




Failure Type

Adhesive – which is failure at the interface
Cohesive – which is failure within the adhesive
Mixed/Thin-film – adhesive and cohesive failure in adhesive joining (near-interface)
Substrate – which is failure within the substrate
Weld pull-out - welds fail through the weld nugget

Figure 1: Adhesive failure modes



Source: Prof Steven Abbott

References

Audi. (2017, April 5). *TechDay Body Structure*. Retrieved from Audi Media Center: https://www.audi-mediacenter.com/en/presskits/techday-body-structure-7469

Autoline TV. (2019, December 13). *2020 Corvette Chief Engineer Talks C8 Stingray*. Retrieved from Autoline: www.autoline.tv/journal/?p=65089

Baron, J., & Modi, S. (2016). *Assessing the Fleet-wide Material Technology and Costs to Lightweight Vehicles.* Ann Arbor: CAR.

Carey, R. (2019, July 2). *The Cars that Made America*. Retrieved from History: https://www.history.com/news/the-cars-that-made-america#section_4

Flink, J. J. (1990). The Automobile Age. 213.

Ford. (2015). *2015 Ford F-150*. Retrieved from Ford Media Center: https://media.ford/com/content/fordmedia/fna/us/en/products/trucks/f-150/2015-f-150.html

General Motors. (2012, August 8). *Fibeglass to Carbon Fiber: Corvette's Lightweight Legacy*. Retrieved from GM: https://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2012/Aug/0816_corvette.html

Modi, S. (2016). *Material Qualification in the Automotive Industry.* Ann Arbor: CAR.

Modi, S., Spulber, A., & Jin, J. (2018). *Impact of Automated, Connected, Electric, and Shared (ACES) Vehicles on Design, Materials, Manufacturing, and Business Models.* Ann Arbor: CAR.

Modi, S., Stevens, M., & Chess, M. (2017). *Mixed Material Joining Advancements and Challenges.* Ann Arbor: CAR.

Barnes T A and Pashby I R (2000a), 'Joining techniques for aluminum spaceframes used in automobiles. Part I – solid and liquid phase welding', *Journal of Materials Processing Technology,* 99, 62–71.

Barnes T A and Pashby I R (2000b), 'Joining techniques for aluminum spaceframes used in automobiles. Part II – adhesive bonding and mechanical fasteners', *Journal of Materials Processing Technology,* 99, 72–79.

Ghosh D, Pancholi L and Sathaye A (2014), 'Comparative studies of adhesive joints in automotive', *SAE Technical Paper 2014-01-0788*, SAE International

Gullino A, Matteis P and D'Aiuto F (2019), 'Review of aluminum-to steel welding technologies for car-body applications', *Metals*, 9, 315-343

Ling Z, Li Y, Luo Z, Feng Y and Wang Z (2016), 'Resistance element welding of 6061 aluminum alloy to uncoated 22MnMoB boron steel', *Materials and Manufacturing Processes*, 31, 2174-2180.

Mallick, P K (2008), "Joining for Lightweight Vehicles", *Materials, Design and Manufacturing for Lightweight Vehicles*, Woodhead Publishing

Martinsen K, Hu S J and Carlson, B E (2015), 'Joining of dissimilar materials', *CIRP Annals-Manufacturing Technology*, 64, 679-699.

Meschut G, Janzen V and Olfermann T (2014), 'Innovative and highly productive joining technologies for multi-material lightweight car body structures', *J. Materials Engineering and Performance*, 23, 1515-1523.

Meschut G, Matzke M, Hoerhold R and Olfermann T (2014), 'Hybrid technologies for joining ultra-high-strength boron steels with aluminum alloys for lightweight car body structures', *Procedia CIRP*, 23, 19-23.

Shome M and Tumuluru M (2015), Welding and Joining of Advanced High Strength Steels, Woodhead Publishing

Skovron J, Mears L, Ulutan D, Detwiler D, Paolini D, Baeumler B and Claus L (2014), 'Characterization of flow drill screw driving process parameters on joint quality', SAE Technical *Paper 2014-01-2241*, SAE International

Yang Y-P, Orth F, Peterson W and Gould J (2014), 'Accurate spot weld testing for automotive applications', *Advanced Materials and Processes*, ASM International, Nov.-Dec.