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Innovative joining technologies for lightweight material vehicles

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Abstract

The transport industry is one of the most important for society and its economic growth. In Europe, this is especially true for road transport, which is an essential pillar for employment, trade, and economic development. The challenge is to minimize energy and cost and maximize efficiency while ensuring comfort and safety. This is the driving force behind technological progress that with social changes (such as, changing consumer preferences, greater environmental awareness) and political changes is revolutionizing the way people and goods move. Nevertheless, the selection of lightweight materials is negligible; it could involve new manufacturing technologies and joining techniques. Jaguar Land Rover (JLR) has been one of the prominent car producers employing aluminum alloys since 2003. A typical JLR monocoque is characterized by 90% aluminum stampings components made of 5xxx and 6xxx series aluminum alloys. Audi Space Frame (ASF) represents an alternative interpretation of improved lightweight frame architecture, and it is characterized by aluminum for more than 80% with the residual parts in CFRP used for rear panels, tunnel and the components useful to higher torsional stiffness. A 30% weight decrease is reached with respect to traditional steel corresponding elements. This review shows an overview of the challenges and opportunities for automotive body structures in the coming years while maintaining the goal of reducing mass and improving sustainability without increasing costs and impacting safety. This manuscript first evaluates how we can reduce mass in vehicles minimizing the carbon footprint and developing recyclable structures. The potential of new materials will be shown in light of the design constraints and the choice of technology used. The final remarks will discuss opportunities for engineering innovation dictated by this period of great changes and needs.

Keywords

Joining technologies, material behaviour, lightweight vehicle design, mechanical bearing, welding technology

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Introduction

The transport industry is one of the most important for society and its economic growth. In Europe, this is especially true for road transport, which is an essential pillar for employment, trade, and economic development. The challenge is to minimize energy and cost and maximize efficiency while ensuring comfort and safety. This is the driving force behind technological progress that with social changes (such as, changing consumer preferences, greater environmental awareness) and political changes is revolutionizing the way people and goods move.

Next to this, the automotive industry sees high impact with emerging trends that are disrupting the entire value chain. The use of lightweight materials to reduce vehicle mass is becoming even more important in the automotive industry not only to improve handling performance of the vehicles but also to reduce carbon emission in ICEs and extend battery range in EVs.

In this framework, employing lightweight materials to decrease car mass has been taken into consideration as one of the most useful aims.[1] As described by Mayyas et al.[2] a weight saving of 10% can ensure a decrease of more than 30% of the total vehicle weight and 5% in fuel consumption.[3] These are the primary issue of the automotive industry focused on ensuring a substantial weight decrease.

Nevertheless, the adoption of lightweight materials is not negligible; it could involve new manufacturing

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technologies and joining techniques.[4] Jaguar Land Rover (JLR) has been one of the prominent car producers employing aluminum alloys since 2003. A typical JLR monocoque is characterized by 90% aluminum stampings components made of 5xxx and 6xxx series aluminum alloys. Audi Space Frame (ASF) represents an alternative interpretation of improved lightweight frame architecture, and it is characterized by aluminum for more than 80% with the residual parts in Carbon Fiber Reinforced Plastic (CFRP) used for rear panels, tunnel, and the components useful to higher torsional stiffness. A 30% weight decrease is reached with respect to traditional steel corresponding elements.

Regardless of aluminum and CFRP design allowing important weight savings compared to the traditional steel construction, its inclusion involved a substantial transformation of joining processes.

The use of lightweight materials has required the development of new joining technologies due to the need to assemble a variety of materials with different chemical and mechanical properties. The joining technologies are often classified in fusion and non-fusion welding, adhesive bonding and mechanical fastening. Among the fusion welding processes, Resistance Spot Welding (RSW) is undoubtedly the most popular joining procedure applied in automotive products. Even if this method has become well-known for steel, some problems are shown in aluminum welding correlated to the chemical response of aluminum to oxygen in air producing an oxide film on the metal side. Although this oxide film safeguards the metal from corrosion[5] it must be removed to allow for weld growth.[6] Because the oxide film has a higher melting point, significantly higher resistance heating is required to break it down.[7] Therefore, the typical welding current for spot welding of aluminum alloys is double than steel. In addition, the lifetime of electrodes for aluminum alloy spot welding is 2.5–5 times lower compared to steel.[8] Although, numerous researchers have exposed that spot welding of aluminum alloys can assure high-quality joint, the processing conditions for example, current and electrode life make its implementation in a mass vehicle production more challenging.

Adhesive bonding is a joining technology that consist of the application of an adhesive between materials interfaces. The most important rewards of this technique are good stress distribution, and the opportunity to achieve a lower weight's components since the abolition of mechanical fasteners.[9] The most important use of bonding in the automotive industry involves nonstructural elements, and its use for sheet metal parts of a load-bearing component is growing.[1,10] For example, adhesive bonding can be utilized in arrangement with resistance spot welding or self-piercing riveting. Moreover, the long-term durability of the adhesives is still not fully understood[11]

Due to the difficulties in welding aluminum alloys and mixed metal/composites joints and the limitation of adhesive bonding as stand-alone process, mechanical joining (specifically bolt fastening and riveting) has been the key technology to join lightweight materials in automotive.

This review shows an overview of the challenges and opportunities for automotive body structures in the coming years while pursuing the goal of reducing mass and improving sustainability without increasing costs and impacting safety. This review not only provide an outline of emerging technologies in lightweight materials joining but also how the less new technologies have evolved and adapted to meet new challenges in the automotive industry. The potential of new materials will be shown in light of the design constraints and the choice of technology used. The final remarks will discuss opportunities for engineering innovation dictated by this period of great changes and needs.

Fusion welding processes

Numerous welding processes have been developed over the years, so classifying them helps to understand their advantages, disadvantages, and field of application. Ways of classifying those processes are disparate: by energy source, by phase reaction, pressure versus non-pressure welding processes, fusion versus non-fusion welding processes, and others.[12,13] In the present work, in order to detail the different welding processes of interest in the design and manufacturing of lightweight automobile bodies, the classification "Fusion versus Non-Fusion welding process" is used.

In general, in fusion welding, the edges or surfaces of the parts to be joined are heated locally above their melting point. The two materials in contact mix together in a liquid state, creating many bonds after solidification.[14] This section will discuss the following fusion welding processes in more detail: resistance spot welding, arc welding and laser welding.

Resistance spot welding

Resistance spot welding (RSW) is the most common joining method in vehicle body-in-white (BIW) manufacturing. Typically, there are between 2.000 and 6.000 spot welds in a modern vehicle, and this accounts for about 75% of the workload for body assembly.[15,16] The RSW owes its wide use to high operating speeds, its suitability for automation or robotization and its suitability for use in high-volume production.[7,17] As shown in Figure 1, the RSW process involves the insertion of two or more overlapping metal sheets between two water-cooled electrodes, which apply constant pressure on a restricted area of the sheets throughout the process in order to clamp the parts together. Hence, the disadvantage of this

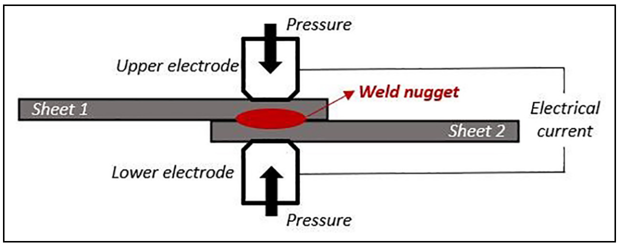

Figure 1. Resistance spot welding (RSW) process.

technology is the requirement to access both sides of the joint. The material is heated by means of electrical resistance. Electrical current is supplied to the workpiece via the two electrodes in a short time. The high contact resistance at the joining surfaces generates heat, causing the localized melting and subsequent coalescence of a small volume of material, forming the weld nugget.

The quality of the joint is determined by the features of the weld nugget, which depends on the process parameters,[18,19] the surface conditions of the sheets in the contact zones, the thermal, mechanical and geometric properties (such as sheets thickness) of the base material and the type of electrode.[17] Concerning this, resistance spot weld joint failure represents one of the main reasons of vehicle crash test failure. The failure of sport welds can affect the torsional stiffness of the vehicle and its performance in terms of comfort and overall safety.[20] For each material mix, there is a current range in which a good weld nugget is produced; excessive heat input can lead to the ejection of the liquid metal from the nugget, while low heat input may result in insufficient melting.[18,19,21]

Although, the process is well established for joining steel sheets, the same cannot be said for joining aluminum alloy sheets, which has rapidly become the material of choice in the design of lightweight and environmentally friendly vehicles. The reason lies in the physical-chemical properties of aluminum. In particular, the following difficulties are highlighted: (i) High energy consumption. This is because aluminum has low electrical resistance and when an uncoated aluminum surface is subjected to the atmosphere, it naturally creates an oxide layer that has a much higher melting point than aluminum and this requires a higher thermal input to create an acceptable weld nugget.[5–7] (ii) Short electrode life. The speed of deterioration of electrodes during resistance spot welding of aluminum is the consequence of high pressure, high temperature and a rapid alloying process. For this, electrode life, that is, the number of welds produced before tip dressing or tip replacement becomes necessary, during RSW of aluminum is in the range of about 400–900 welds,[15] a shorter lifetime than during RSW of steel. Finally, materials with considerable differences in melting temperature cannot be joined using this technology, as in the case of aluminum-steel joining (Melting Point: Steel 1460°C – Aluminum 660°C). Here, the solution usually lies in using interface materials between aluminum and steel, for example, a sheet of aluminum-clad steel can be used as the transition material between the two.[17]

Arc welding

Gas metal arc welding and gas tungsten arc welding. Arc welding techniques such as gas metal arc welding (GMAW –Figure 2(a)), also called metal inert gas (MIG), and gas tungsten arc welding (GTAW – Figure 2(b)), also called tungsten inert gas (TIG), are used in BIW vehicle construction as they have the immediate advantage of being known and proven technologies.

After an adequate design of process parameters, access to only one side of the joint and its high mechanical and quality properties makes this technology widespread. A notable example of the use of arc welding is seen in the production of the Audi A8, where the technique is used in the joining of extruded

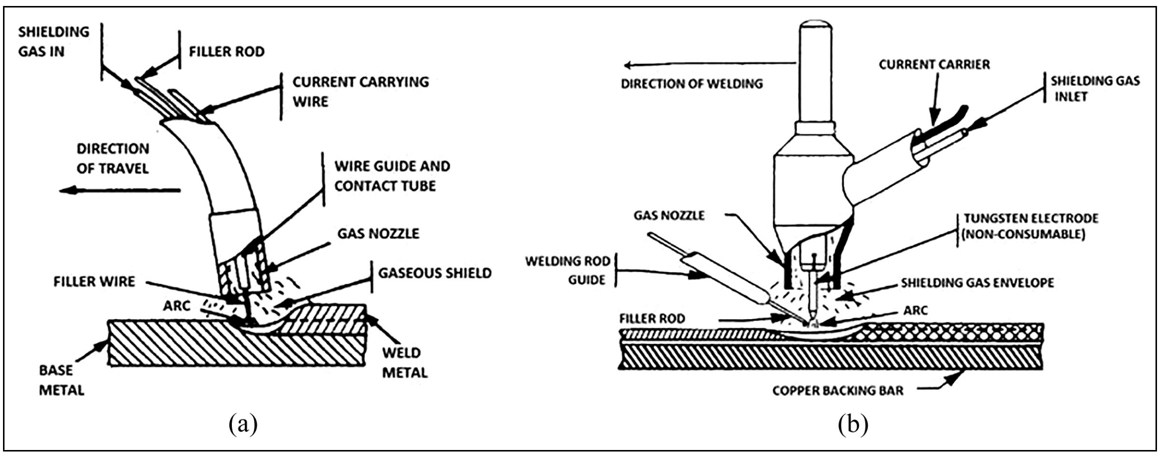

Figure 2. (a) Gas metal arc welding and (b) gas tungsten arc welding.

components to die-cast nodes.[7,22] However, the significant heat input required by the technology results in a not negligible degree of distortion of the parts.[7] Indeed, in a production BIW operation, there are often mating problems between parts due to non-compliance with tolerances.[1] Mainly for this reason (heat-induced distortions), Elise Lotus engineers stated that they did not prefer welding as a joining method.[23]

In arc welding, the heat of an electric arc between the electrode and the parts to be joined is used to melt the metals. The main classification of arc welding technology is made according to the type of electrode: (i) consumable and (ii) non-consumable. In the case of the consumable electrode (i), the electrode not only conducts current but also acts as a filler material itself (as in the case of GMAW –Figure 2(a)). The electrode is a solid wire, the material of which is chosen so that it can optimally match its strength with that of the base metal. In the case of the non-consumable electrode (ii), it only conducts current in the area to be welded (as in the case of GTAW –Figure 2(b)). However, even in the latter case, a filler material may be required but this is inserted into the weld site using a separate rod or wire.[17] In general, the arc produces a temperature of around 3500°C at the tip of the electrode, creating a pool of liquid metal in the welding area. As the pool gradually solidifies, a metallurgical bond is created between adjacent parts. The welding parameters that affect the final quality of the welding joint are arc current, arc voltage, wire feed rate, electrode travel speed and current density and preheating temperature.

Arc welding also satisfies the feasibility requirements to be able to be automated. In addition to increased productivity, these developments in process automation represent a crucial point in safeguarding the health of operators, who will just supervise the process, from the fumes produced by arc welding.

In the automotive industry, arc welding is used with both aluminum and steel. However, arc welding of aluminum suffers from the presence of the oxide layer that forms on its surface.[24,25] Therefore, the oxide layer should be removed beforehand. The gas metal arc welding (GMAW) is also used to join dissimilar materials with comparable melting points. It is understood that it is not feasible to employ the technology as is to join steel and aluminum. For new lightweight concepts in automotive construction, it is no longer possible to rely solely on traditional welding techniques (including MIG and TIG). This is because combining multiple materials is now the order of the day for minimizing weight and maximizing mechanical strength requirements. Therefore, research is intensively focusing on optimizing existing technologies to meet new challenges.[26] For example, in Refs.[27,28] are studied respectively the gas tungsten arc welding of aluminum alloy to galvanized steel with Al-Si, Al-Cu, Al-Si-Cu, and Zn-Al filler wires and the assemblies between galvanized steel and aluminum alloy using gas tungsten arc welding, with lap and overlap configurations and two different heating strategies.

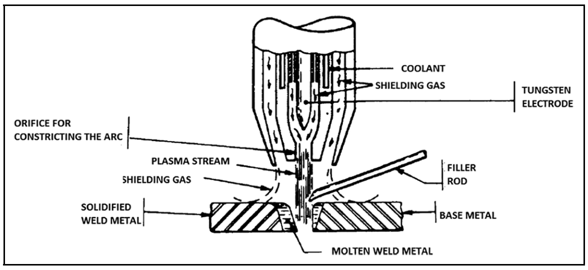

Figure 3. Plasma arc welding.

Plasma arc welding. Plasma arc welding (PAW) falls into the class of non-consumable electrode arc welding processes. Plasma arc welding finds use in the automotive industry, where it is preferred over other welding solutions for joining structural parts made of different materials and the steel pipes of the exhaust system.[29] Plasma arc welding technology is schematically shown in Figure 3. The process is very similar to gas tungsten arc welding, from which it differs in the presence of a converging nozzle that reduces the arc cross-sectional area, increasing its energy density, plasma velocity (approaching to the sound velocity) and temperature (to about 25.000°C).[30] Also in plasma arc welding, the electrode is made of tungsten with the difference that it is placed inside the welding torch, which protect it from the external environment. This increases the useful life of the electrode representing an important advantage in terms of increased productivity and decreased downtime. When the inert gas is invested by the electric arc established between the electrode and the workpiece, it ionized and forms plasma arc. Energy associated with plasma depends on plasma welding current, size of the nozzle and plasma gas flow rate.[13] The strongly concentrated high thermal energy reduces the weld bead width and increases beam penetration, allowing even workpieces with greater thicknesses to be joined successfully. The ability to modulate the current supplied is an advantage both in terms of controlling energy consumption and in terms of the versatility of the technology. In particular, depending on the plasma forming current, three different types of plasma arc welding can be distinguished: (i) micro plasma arc welding ($I_p < 15\ A$) suitable for thin sheets, (ii) melt-in mode plasma arc welding ($15A < I_p < 400A$) suitable for sheet up to 2.4 mm thick, and (iii) keyhole mode plasma arc welding ($I_p > 400\ A$) for the thickness of sheet greater than 2.5 mm.

High-energy beam welding

The two main types of high-energy density welding processes are electron beam welding (EBW) and laser

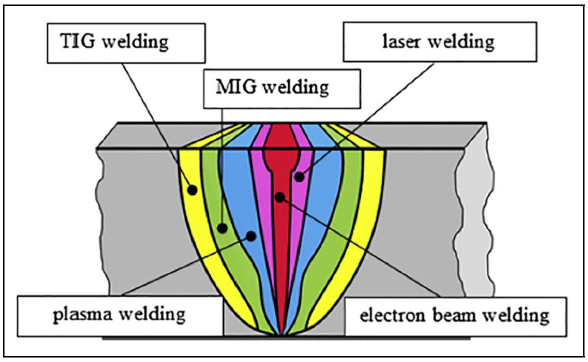

Figure 4. Comparison of the weld bead shape produced by fusion welding technologies.[31]

beam welding (LBW); the first uses the energy of an electron beam, and the second a CO_2 or Nd:YAG laser beam. Both processes use a high energy density beam to melt the joint area of two components but differ in the way the beam is focused using electromagnetic lenses for electron beam welding or optics for laser beam welding. The energy density in these processes is about 10^{10}–10^{13} W per m^2.[12] Both processes are widely used in the automotive industry where the need to expand production volumes is a constant challenge to implement new or improved technologies. In particular, the EBW is used to weld elements of gear transmissions, engine housings, detectors, radiators, crankshafts, piston rods, valve heads, filters, catalysts, turbo-compressors, wheel rims, airbags, and many others[31]; while recent applications of LBW involve not only the joining of delicate parts or difficult metals but also the manufacture of tailored blanks in automobile body construction with a sheet of varying thicknesses.[17] In electron beam welding, free electrons emitted from the cathode are accelerated and focused by electric and magnetic fields that define their path in order to project them directly onto the workpiece. Such a defined beam with high energy density not only produces a narrow, deep weld bead but also reduces the deformation of the workpiece. This concept is emphasized in Figure 4 where the comparison of different weld bead shapes obtained by fusion welding technologies is shown.

At the same time, a strong disadvantage of the technology is the need to propagate the electron beam inside a vacuum chamber since in air the propagation would be short.[25] In this regard, research has taken important steps in order to overcome this problem. In fact, non-vacuum electron beam welding has been pioneered in the automotive industry.[32,33] Here, the electron beam, passing through several pressure chambers, is gradually brought to atmospheric pressure. Certainly, as the electrons leave the nozzle, they collide with air particles and are deflected; therefore, the distance between the nozzle and the workpiece should be limited so as not to compromise positioning tolerances.

Laser beam welding overcomes this problem, in fact the laser beam can be effectively transmitted through the air without the need for vacuum chambers, this and other advantages make laser beam welding particularly attractive for the automotive industry. First, because the laser beam is sharply focused, a high energy density is produced, resulting in a narrow deep weld bead. In addition to good geometric characteristics, the bead is of high quality and in steel, it exhibits good formability. More, LBW is ideally suited for automation, representing strength for modern Industry 4.0; in particular, with Nd:YAG lasers, the laser beam can be transmitted using fiber optic cables, providing the ability to be remotely manipulated by a robot in addition to the advantage of effortlessly reaching points of complex workpiece geometries.[1,7,17] Both steel and aluminum parts can be welded with this technology; however, aluminum is significantly more difficult to laser weld than steel due to the lower adsorption capacity of the laser beam on the surface of this metal. In addition, aluminum has high thermal conductivity, which easily causes heat to be lost from the welding area. Without optimized laser welding process parameters, solidification cracking, loss of bonding elements (e.g. Mg and Zn), and porosity can occur.

Non-fusion welding processes

Non-fusion welding processes accomplish welding primarily through plastic deformation by the application of pressure or friction generation at temperatures below the melting point of the base materials. Welding of different materials is still difficult if not impossible in some cases due to the different thermo-mechanical properties of the materials. Solid-state welding is therefore a subject of interest and continuous research by the scientific community.

Friction stir welding and friction stir spot welding

The growing demand for energy and environmental issues have focused the attention of manufacturing industries on the search for sustainable processes and innovative materials. Regarding this, the automotive industry is focusing on finding innovative lightweight materials with high strength-to-weight ratio to minimize fuel consumption.[34] New materials require new or improved technologies. Friction stir welding (FSW) and friction stir spot welding (FSSW) are two technologies that meet the above requirements and are a valid alternative to several traditional welding methods for body-in-white (BIW) car structures to reduce the weight and manufacturing costs without compromising passenger comfort and safety. This is because both processes take advantage of the plastic deformation of materials to form a metallurgical bond without the use of filler material and thus without the need to reach the melting temperature of

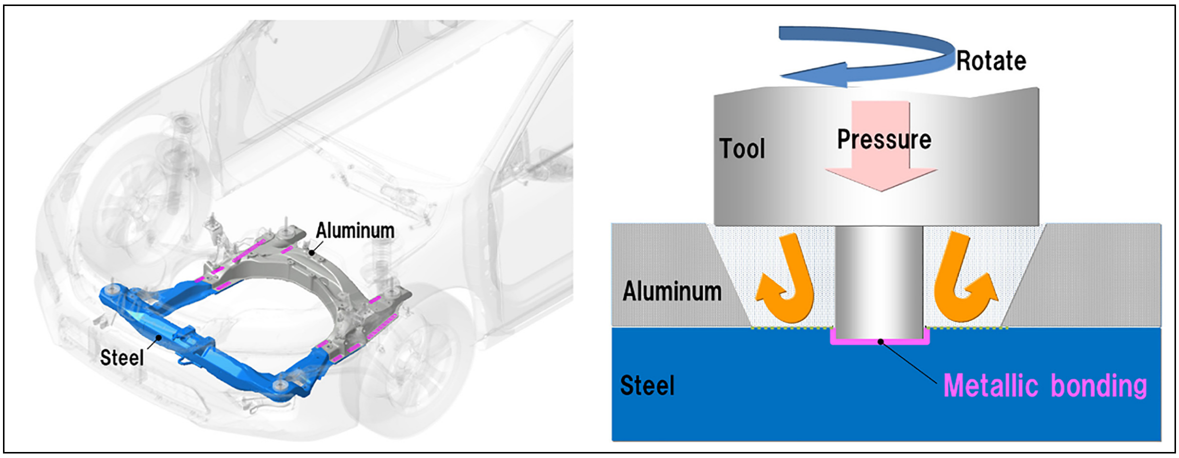

Figure 5. Honda Motor Co. – Application of friction stir welding and conceptual diagram of FSW of dissimilar metals.[39]

materials; therefore, the process is more energy efficient, as it uses only a fraction of the energy required for fusion welding,[35] which eliminates the problems of cracking, porosity, formation of second phases, and thermal distortions stemming from heat input.[34,36] In this case, a non-consumable rotary tool with a properly designed pin and shoulder is progressively pressed against the surface of the workpiece. The heat generated by friction between the tool and the workpiece causes localized softening resulting in plastic deformation at high strain rates. The axial force decreases when the workpiece reaches the critical temperature for plastic flow and the tool moves along the joint line (FSW), facilitating mixing and flow of the plasticized material and leaving the material formed and recrystallized. The FSSW was developed on the basis of the FSW, from which it differs mainly in the absence of tool translation movement; this results in two different fields of application: the FSSW is used for spot welding, while the FSW for linear joints. In these terms, the FSSW finds greater use in BIW structures, where spot welds are prevalent over flat rectilinear joints.[17] The mechanical concept and non-melting of materials, make the technology flexible and applicable to joining dissimilar materials, a new trend to pursue the challenge of vehicle weight reduction. In addition, both friction stir welding and friction stir spot welding are scalable to automated solutions with robots resulting in a significant increase in production.[37] Sheet metal body and engine support frames can be friction welded: bumper beams, air suspension systems, intake manifolds and much more.[38] The undoubted advantages of this technology have always made it particularly attractive to major vehicle manufacturers, for example, Mazda first employed it in 2003 in the rear door panels of the Mazda RX-8 and later in 2005 for the Mazda MX-5 sports car.[36] Honda has successfully employed FSW for welding steel and aluminum in the suspension system of its vehicle in mass production by moving a rotating tool on the top of the aluminum which is lapped over the steel with high pressure (Figure 5).[35,39]

Magnetic pulse welding and ultrasonic welding

Two other solid-state welding technologies of interest to the automotive industry are Magnetic pulse welding (MPW) and Ultrasonic welding (USW). Magnetic pulse welding (MPW) uses electromagnetic pressure to accelerate a workpiece and produce an impact against another workpiece with a such high kinetic energy that, when the two collide, enough pressure is generated to create a weld. The main use of magnetic pulse welding involves joining hybrid tubular structures.[41] In fact, Dana, a large US group working on magnetic pulse welding, was optimistic about designing space structures that combine the strength of steel and the lightness of aluminum, overcoming obsolete single-material structures. Also Pulsar, small Israeli company which is part of the massive Clal Industries group, has employed magnetic pulse welding to weld aluminum fuel filters, tubular seat components of steel and aluminum materials, transmission shafts, and hydroformed parts.[42,43] Ultrasonic welding, on the other hand, uses high-frequency ultrasonic energy to produce low-amplitude mechanical vibrations. By clamping the parts under pressure, the mechanical vibrations generate heat at the interface producing a metallurgical bond without melting the base material. Ultrasonic welding finds its main use in joining electric vehicle battery components and in joining several stranded copper cables into a single junction, used in the automotive wire "harnesses."[44,45]

Mechanical joining

In the automotive industry, traditional mechanical joints involving bolts and screws are not common for large assembly, such as the vehicle body. The main reason lies in the high cycle time and labor intensive operations. In fact, the parts must be preliminarily drilled, and only after the components are correctly positioned can the fastener be inserted. In addition, the precision of the pre-holes on the two (or more)

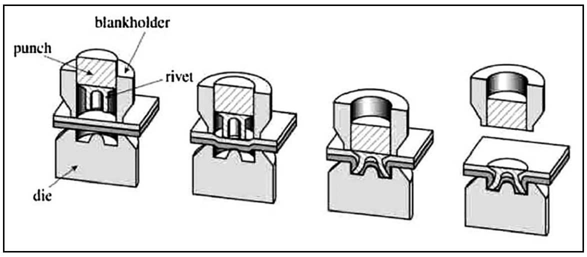

Figure 6. Self-piercing riveting process.[40]

parts to be joined must be high to avoid problems in the assembly operations. For large assemblies such as body-in-white vehicles, welding is certainly more competitive than traditional mechanical joining methods which are at most used for chassis and suspension parts. An exception is self-drilling rivets EJOT[46] in which the hole is produced by an integrated drilling/forming head (Figure 6). They represent a good compromise when only one side of the joint is accessible. Good potential for automotive applications, on the other hand, is shown by self-piercing riveting and clinching.

Self-piercing riveting and clinching

Essentially, the SPR is a cold-forming process. It is a quick, inexpensive, one-step technique that performs the jointing; in fact, no holes are required. In addition, the SPR process is easily automated with robots, which greatly increases the production rate.[47] Audi was a pioneer in the use of self-piercing riveting technology first in the Audi A8 to join aluminum structural panels and then in the Audi A2 in the space frame structure.[48] Later, Jaguar also applied mechanical joining in the monocoque of the Jaguar X350 model.[49,50] Rivets are pushed directly into plates clamped between a blankholder and a die. The punch pushes the rivet that penetrates the upper plate, and the shape of the die causes the rivet deformation inside the lower plate producing a mechanical interlock between two (or more) plates.

It is clear that the technology has no problems in joining dissimilar materials which makes it fully focused on the new challenges of the automotive industry. It is well suited for joining those materials such as aluminum and magnesium alloys that present significant difficulties with the welding process. Contextually, there are some disadvantages: access to both sides of the joint; the mechanical properties of the substrate materials to receive the fastener, a relatively high forming force (typically of the order of about 40 kN) that must be properly designed and calibrated in order not to induce cracks in the material that would cause a relevant reduction in the fatigue life of the joint and of the structural part.[46,51] Clinching joining differs from the self-piercing riveting process substantially only in the absence of the physical fastener. In fact, mechanical interlocking is produced by the plastic deformation of the plates which, assuming a particular shape, allows the relative locking of the parts. The absence of the physical fastener makes clinching more economical than self-piercing riveting especially for high-volume production in the automotive industry, where the total production cost increases proportionally to the number of joints.[51]

Adhesive bonding technologies

In recent decades, in the industrial sector and especially in the automotive field, adhesive bonding processes have been increasingly used as an alternative to traditional assembly technologies. This growth is due to two main reasons: the first is environmental, the second is linked to the excellent properties of the adhesives and costs. In fact, the European Commission has introduced new rules that impose the progressive reduction of noxious exhaust gas emissions.[52,53] Weight reduction is one of the possible strategies to match the prescribed emission limits. Replacing the joint by welding or bolts with adhesives is particularly interesting, even if this technique offers a modest contribution to reducing vehicle weight. Furthermore, the aforementioned possibility of gluing materials of different nature, such as high-strength steel or aluminum to composite materials, allows for a high saving in weight. Indeed, studies show that by reducing the weight of a vehicle by 100 kg, CO2 emissions can be reduced by 3%–5%.[52]

First of all, the adhesives allow to reduce noise and vibrations by ensuring a more uniform distribution of stresses compared to joints by spot welding and bolting and can offer a joint stiffness comparable to that of traditional joints. Furthermore, they allow hybrid joints to be made by gluing different materials, such as metallic materials and composite materials, and guarantee the possibility of gluing light materials, such as composite materials, with positive effects in lightening the total weight of the vehicle and in the process of production. In fact, the simplicity of the adhesive bonding process guarantees a simplification of the production lay-outs with less space occupied in the factory and a reduction in the equipment used.

Hot-melt adhesive

Hot-melt adhesive (HMA) is a thermoplastic compound and exhibits its adhesive capabilities in the liquid state. In the cooling curve of a hot-melt adhesive three phases are indicated: liquid, plastic and solid. The molten adhesive (approximately 160°C) is brought into contact with the substrates to be bonded and a thermal gradient is generated in the system causing heat transfer across the substrate area, the temperature decreases and the adhesive it restores its solid state by acquiring a cohesive force which keeps the two members united. Cooling occurs naturally in a few seconds and this feature makes the HMA particularly interesting for the automotive sector where production speed is essential. Although HMA is a thermoplastic adhesive and compared to thermosetting adhesives it has a lower mechanical strength and a lower operating temperature, due to its versatility, short production times and good bond strength its use in the sector has grown from 70s to today. Another winning feature for the use of hot-melt adhesives in this sector is the possibility of joining components of different materials, reducing costs, production times and weight.

Disassembly issue

The difficulty in separating the adherends without damaging the involved surfaces could represent an obstacle in the use of adhesives. There are several technologies that allow the disassembly of a glued joint, such as mechanical cutting or the use of acids and solvents, but these cause damage to the parts making it difficult and sometimes impossible to reuse them.[9] In this regard, new technologies are being studied to find a solution to this problem. One of these concerns the heating by electromagnetic induction of a nano-modified thermoplastic adhesive.[52] In particular, the adhesive in question is a hot-melt adhesive which is loaded with nanofillers sensitive to electromagnetic fields and through an inductor the nanoparticles are able to increase their temperature due to the losses dependent on the generated electromagnetic fields and allow to reach the melting of the adhesive. A second technology involves the use of microwaves as a mean of creating the electromagnetic field. The heating of the adhesive up to its melting temperature is due to the movement of the electrons sensitive to the generated field, resistive heating, the reorientation of the electrons and the presence of permanent dipoles.[54] Such technology would allow for the possibility of separating glued components, making it possible to reuse parts at the end of the vehicle life, but they also offer an effective solution to incorrect joints during production and allow for the easy replacement of damaged parts. The higher cost due to the addition of nanoparticles in the adhesive, therefore, is justified by the economic, environmental and process advantages deriving from the possibility of having reversible glued joints.

Joining of automotive lightweight structures in the future

Given the current regulations, any development in mobility must consider the necessary reduction of pollutant. Weight is a key element for vehicle manufactures and the selection of the right material for any specific application is becoming a key focus during the design and manufacturing phases. Several market research forecast increasing use and application of composites. However, further developments are required to enhance the use of composites in mass a production vehicle manufacturing. We will quickly enter a market where demand is greater than today and probably only those players who have been able to innovate, taking advantage of economies of scale, will remain.

The need for high rigidity and mechanical resistance has determined two clear trends in composites material for automotive applications: carbon fiber and glass fiber reinforced materials (CFRP and GFRP). These materials usually have high characteristics of rigidity and strength, thus allowing the production of lightweight body structures.

Complex challenges for joining

However, the application of CFRP and GFRF present new challenges to joining technology. In particular when composite materials need to be joined to other substrate materials. Drilling such materials by screwing or riveting is not only demanding, but damages their laminar structure, which is a key part of their strength. In addition, the hole must be carefully sealed, otherwise, delamination of the material could occur at this point. The connection of CFRP and metal also carries a high risk of corrosion.

For stable joints and efficient processes, it is also necessary that the laminate product is intact; for this reason, welding is often evaluated as a joining method. However, this method has significant drawbacks: in addition to the high energy consumption, it is only suitable for materials with a thermoplastic matrix.

For joining composite material to other components, it is therefore advisable to rely on another joining method that is, adhesive bonding. It is not only a non-damaging joining technique, but also provides flexibility of combination with different substrate materials and good resistance to dynamic forces. Furthermore, bonding is a process that can be automated, which offers a significant advantage in terms of reduced cycle time. Therefore, it meets the typical requirements of industrial production, including those of the automotive sector.

Combine glue and screws

For the joining of composite materials with other materials, the company Böllhoff, specialist in inserts, and the company DELO, expert in the field of adhesives, have developed an alternative bonded bolt technology called ONSERT that uses stud welding as its basis.

To avoid complex drilling, screwing or riveting, threaded bolts are bonded to fiber composite materials instead of being welded.[55] With ONSERT, the most appropriate combination of pin and base geometry is designed. The method involves first applying an adhesive to the underside of the base, which is then bonded to the composite material. The thickness of the adhesive layer is set using spacers, the so-called spacers, and is usually 0.1–0.2 mm.

The peculiarity of this method is the speed of application: in fact, the base is made of amorphous material, which has a translucent surface and therefore guarantees reduced cycle times. Hardening takes place via a LED lamp in about 4 s and can be fully automated. The joint formed can be stressed immediately and the plastic part quickly obtains a stable thread to be screwed and unscrewed freely as needed.

Polycarbonate, polyamide or polyethersulfone can be used as material for the transparent base of the ONSERT, depending on the mechanical characteristics required and the environmental conditions of use. These must only be amorphous plastics, as these allow enough blue light with a wavelength of 400 nm to pass through, which is necessary for the adhesive to harden.

ONSERT are suitable for a variety of applications, especially when components need to be fixed without structurally joining them. Hundreds of thousands of aircraft pins are fitted to aircraft each year. In this way it is possible, for example, to fix cover plates, insulating materials and floor panels; in the future, ONSERT could also be used for fastening these types of parts.

CFRP is increasingly being used in automotive construction, especially for B-pillars and C-pillars. For example, thanks to ONSERT it was possible to fix a group of power cables to these posts. Other possible applications are the bonding of clips, holders for sensors or accessories. Furthermore, this method can be considered as an alternative to welding, since it has greater flexibility for production compared to the latter. In contrast to welded points, in fact, glued points can be easily modified even after the construction is complete.

To test the suitability of the method for such applications, Böllhoff and DELO bonded CFRP and other materials with ONSERT technology, then subjecting these joints to a number of tests common in the industry, such as the 85/85 test, where the components are stored at a temperature of 85°C and an air humidity of 85%, and the VDA climate test.

In this respect, it has been demonstrated that the ONSERT can achieve high values of tensile and shear strength of the threaded foot, withstanding even the most demanding test conditions.

The two tests also demonstrated the stability of the ONSERT after 1.000 h of testing in salt spray and after 4 weeks of immersion in Skydrol, a hydraulic fluid used in aeronautics. Despite exposure to such atmospheric agents, there was no significant decrease in the strength of the fitting. Finally, DELO and Böllhoff also examined the thread failure torque on a CFRP surface at room temperature. The obtained value of 9 Nm is significantly higher than the standard for the tightening torque of the M5 threads, the value of which amounts to 5.5 Nm and whose dimensions are comparable to those of the ONSERT used.

Thanks to ONSERT, Böllhoff and DELO have developed a fast and safe combination of adhesive technology and loosening screw connections that combines the best of both worlds.

Conclusions

This review shows an overview of the challenges and opportunities for automotive body structure manufacturers in the coming years while maintaining the goal of reducing mass and improving sustainability. New concepts for decreasing the mass of automobiles are overflowing, but continuous research and financial funding is necessary to get them to business experience. Several OEMs and academic institutions have demonstrated interest in this question and technological resolutions are being built and developed.

Nevertheless, it is crucial to mention that these analyses are essential for the development of the next-generation automobiles. The new concepts to reduce vehicle mass need to be assessed with both theoretical and experimental strategies, and as an automobile's mass of body structure decreases, this will inevitably allow light-weighting of other components. This will create new trends in terms of design, manufacturing and final assembly of the vehicles. Engineers must evaluate ever greater specifications of the materials and of the machining and joining processes used. Only well-established and reliable techniques will be introduced in the realization of new concepts for lighter and more performing vehicles. These techniques also require detailed assessment of the business cases for a successful implementation in a world class manufacturing environment.

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