Key technologies welding and joining

Prof. Dr.-Ing. Ulrich Dilthey

President of the International Institute of Welding -IIW
ISF - Welding and Joining Institute, RWTH - Aachen
office@isf.rwth-aachen.de

Keywords

Key Technologies, Arc Welding, Electron Beam Welding, Non Vac EB-Welding, Laser Beam Welding, Laser-MIG-Hybrid Welding, Spot Welding, Mechanical Joining, Adhesive Bonding, Commercial Relevance of Joining Techniques

1. Introduction

There are not many things in our natural environment which have the monolithic structure and the beauty of a rock crystal. Most things of our environment are, for that matter, composed of many individual parts and those parts must be joined to one piece -be it immovable or movable - in order to fulfil their function as a structural part.

Three recognized key technologies and their relatedness to joining techniques shall be considered.

The first key technology is "Traffic", Figure 1:

A car is composed of many single parts which are kept together by thousands of welding spots and many metres of weld seams and, nowadays, more and more by hundreds of meters of adhesive bonds. Vehicles which are used for rail traffic like, for example, an ICE high speed train wagon, are, of course, welded. The ICE wagon has a length of more than 20 metres and is composed of more than twenty individual extruded profiles which are welded together with the suitable joining technologies. Interestingly, the window openings are

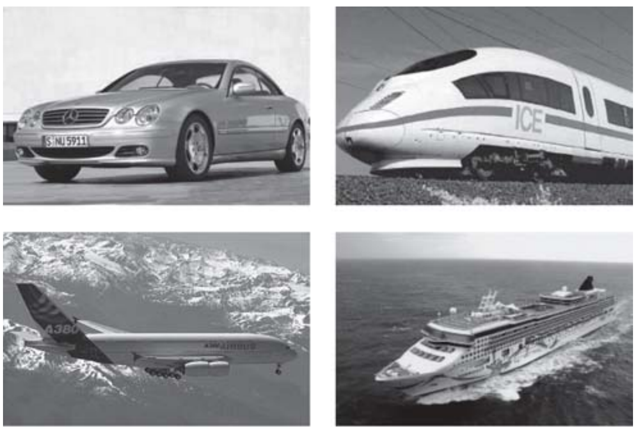

Figure 1. Key technology "traffic"

cut out with the laser only after the wagon has been welded completely. In air traffic the mainly used technique is riveting; for the new airbus 380, however, a large part of outer hull elements has been welded, for the first time with the laser. A cruise ship consists of more than 300,000 single parts, and 900 km of welding seams must be welded for assembling the ship. Nowadays, but also when looking ahead, the key technology "traffic" is, in conclusion, not imaginable without the application of welding.

The second key technology is power-and civil engineering

A power plant produces energy. For the generation of profitable and that means highly efficient energy the so-called steam parameters are important: a highest possible pressure with, at the same time, high steam temperatures. The boilers, pipes and turbines must be capable to tolerate those high pressures and temperatures. This is only possible through the selection of suitable materials and joining techniques. In the field of chemical apparatus engineering, corrosion susceptibility creates extremely challenging tasks. Aggressive media, like acids and bases, mainly in processes with extremely high pressures and extremely low or high temperatures, are dealt with only through the application of special materials which again make extremely high demands on the joining technique. It also applies to the field of civil engineering that steel structures are of course, not accomplished without welding, as the picture of the Öresund bridge shows. But even if the used steel is not visible, think of concrete highrises, massive steel structures inside the highrises are responsible for the strength and safety of those buildings, and it goes without saying that the steel has been welded. Without welding, power- and civil engineering would also be impossible to realise.

The third key technology is the microsystems technique

Smallest, sometimes no longer visible sub-assemblies (modules) must be joined. Modern electronics and computer technology are nowadays just unthinkable without the use of sophisticated brazing techniques. Thousands of brazing spots on a most confined space are necessary to make a computer work, a mobile phone has more than thousand brazing spots and would, of course, not work without them. The sensors, actors and chips from Figure 3 have all been joined with most different technologies. The microsystems technique is not accomplishable without using joining technology and will, also in future, not be possible.

The joining technique is capable to bridge nine dimensions, from 10^3 up to 10^{-6}; the modern joining technique provides technologies which are absolutely indispensable - and this covers the range from ship to chip. The joining techniques belong to the key technologies for the future.

Development of Joining Technologies

Nature itself has created versatile joining techniques. The cross spider's web, a termite hill or the sundew are just representing a few examples.

Also with regard to utilisation by humans, the joining technology is an ancient technology. Artefacts from Mesopotamia, dating back to 2,500 B.C., have shown that joining techniques had been used already for creating jewellery or basic commodities. Artefacts from all over the world, from China, Europe or South America are documenting the worldwide and early application of the joining technique.

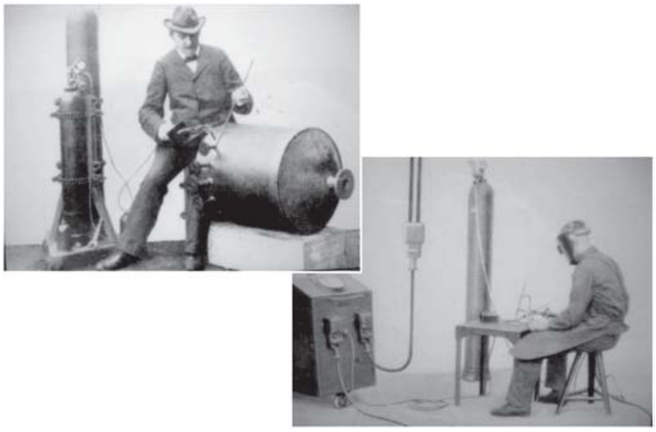

Figure 2. Beginning of modern Joining Technology

Modern welding techniques have been first applied at around 1850 with the use of an oxyacetylene flame (acetylene and oxygen) for the fusion of the materials to be joined. By the end of the 19^{th} century for the first time the energy of an electric arc had been used for melting the materials, Figure 2. These methods are still existing to this day and they have in the past been constantly improved and modified.

2. Welding processes

2.1. Trends in Arc-Welding Processes

In the early sixties, GMA Welding methods were introduced into industrial manufacturing and they have been consequently developed further ever since. Great efforts have been made to increase deposition rates and with this increasing efficiency and welding speeds and decreasing heat input by extending the frontiers of known processes and by developing new ones.

2.1.1. GMA-Welding Processes

Modern electronics and computer control as well as improvements in wire feeding have led to digitally controlled power with high power/weight ratios with new features. Digital controllers allow the flexible implementing of several, very different power-source characteristics containing complex control strategies. Pulsed Arc welding control strategies have been improved concerning process stability and avoiding and recovery from short circuits. Using digital controllers makes interfacing to external computers a lot easier, so that modern power sources provide multiple functions for adjusting process characteristics, parameter development and documentation and as well as for quality assurance.

These machines allow the use of all stable welding processes beginning with the well-known short arc welding process up to the high deposition welding processes such as the rotating-arc and high-deposition spray arc welding processes.

2.1.2. Two-Wire Welding

GMA Welding with one wire has, applying the mentioned types of arc, reached operating ranges, that probably can not be extended significantly by further developments of power-sources, filler materials or shielding gases. Literature mentions welding speeds of up to two m/min for high deposition short arc welding, as well as deposition rates of up to 14 kg/h for the rotating arc. A further increase in deposition efficiency is, among other reasons, limited by the instable arc rotation.

This and the need for high deposition rates with reduced heat input led to the development of the GMA-two-wire-welding-technology, combining two wire electrodes in one common gas nozzle. Early investigations on this field carried out in the 1975 failed as the power source technology at that time was not able to maintain a stable welding process. The application of a new generation of power sources, however, was able to overcome the witnessed difficulties and establish two-wire welding in 2 variations as a promising new production method in industry. Employing a second process has significant influence on the shape of the weld pool. Arranging the electrodes behind each other stretches the welding pool in the direction of the welding speed. The leading wire then causes adequate penetration while bead shape is determined by the trailing wire electrode. The longed weld pool allows better degasification, a fact which, especially in welding of aluminium and in welding through primer coatings, reduces porosity sensitivity. Twisting the electrodes slightly into a position next to each other enhances bridging abilities at reduced current levels. This, however, affects the weld speed. A twist by about 20°requires a reduction of weld speed by about 25 -30%.

GMA-two-wire welding processes are divided into two variants, twin-GMA Welding, which is the older process employing a common contact tube and tandem-GMA welding, which uses electrically isolated contact tubes for each wire.

2.1.3. Twin-GMA Technology

Developments started with the twin-GMA technology, which is characterised by a common contact tube connected to one (or two coupled) power-source. This results into the same voltage being applied to both wire electrodes. As two equi-directional current-carrying conductors are attracted to each other due to the magnetic forces, the arc roots of both electrodes form (depending on the distance between them) a common root. At a spacing of 4 to 7 mm, depending on wire diameter and total current intensity, the detached droplets meet in one common weld pool. Smaller distances may lead to a droplet bridge between both electrodes, causing process instabilities. In case of a too large distance between the wires, to separate weld pools occur and because of heavy blow effects, heavy spatter occurs.

Main disadvantage of this process variant is, that the welding parameters can not be set independently for each electrode, so that individual wire speeds and wire diameters cannot be used. Moreover, short circuiting of one arc will extinguish the other because of the common contact tube, making the overall process instable. This limits twin GMA-welding to non-short circuiting processes such as spray-arc or pulsed arc.

2.1.4. Tandem GMA Welding

In order to optimise process behaviour and to be able to control both arcs separately, torches with electrically isolated contact tubes are used and synchronized independently controllable power sources are employed, Figure 3. Such it is possible to use this process in short arc welding and to use different wire diameters and speeds, were necessary, featuring stable welding processes.

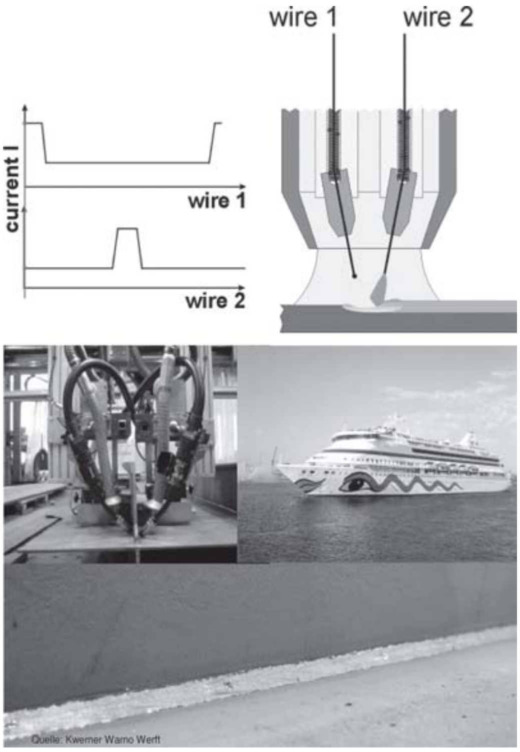

Figure 3. GMA Tandem Welding Technology

2.1.5. AC-MIG Welding

The need for lighter constructions leads to the use of thinner sheets, which in turn, results in difficult gap bridging ability. When GMA welding with reverse polarity, heat input into the base material as well as penetration is reduced and the ability to bridge gaps improves. Unfortunately process stability is bad with reverse polarity. AC-MIG-powers sources combine a standard pulse process with an adjustable phase of reverse polarity. This leads to a stable welding process with adjustable penetration and gap bridging ability highly suited for thin sheets with gaps as often found in industrial applications.

2.1.6. CMT Processes

CMT is the abbreviation for "cold metal transfer" and specifies a GMA process with a very low heat input, in comparison with the conventional short-arc process.

In the conventional short-arc process, the wire is continuously fed. At the moment of the short-circuit, the current increases strongly and is responsible for the circuit breaking and for arc re-ignition. The high current intensity at the moment of arc re-ignition and the rather uncontrolled breaking of the circuit causes increased spattering.

In a CMT process the wire is not only moved into the direction of the workpiece but also, with oscillating wire movement and frequencies of up to 70 Hertz, withdrawn from the workpiece. The wire movement is thus a part of the process control.

The short-arc current of the CMT process is very low, the material transfer occurs with a current of almost zero. The short-circuit is, in addition, not breaking uncontrolled but is effected and controlled by the wire withdrawal. Both properties cause a low energy input with practically spatter-free welded and brazed seams.

The main application fields of the CMT process are: spatter-free MIG brazing, thin sheet welding (aluminium, steel and high-grade steel) and arc joining of steel with aluminium.

2.1.7. GMA-Brazing

The principle difference between GMA welding and GMA brazing lies in the field of metallurgy. When welding, a certain amount of penetration is desired, to ensure fusion between base material and steel filler material. In brazing, there should be no melting of base material, if possible. GMA brazing equipment is the same as for GMA welding, merely a low-melting copper base bronze wire (900°-1100°C) is used. Processes used are short arc as well as pulsed arc.

GMA-brazing has already become well established as a method for joining galvanised thin sheets. As no base material should be melted, heat input into the material is minimised and damage to the zinc coating is limited to a minimum with no negative influence on corrosion properties, Figure 4.

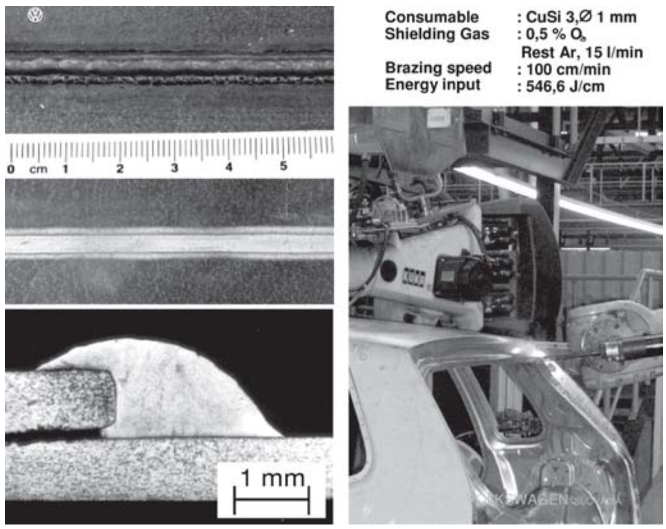

Figure 4. GMA Brazing

The strength of the brazing joints is comparable to that of welds. Moreover, finishing of the brazed seam is easy. Due to this, GMA brazing is becoming more and more popular not only for car body building in automotive industry but everywhere where the advantages of low heat input, low distortion, less damage to galvanised coatings and high brazing speeds outrule the higher price of the required bronze electrode.

2.1.8. Plasma-MIG Welding

Plasma-MIG welding is a welding process, that is experiencing a revival after being developed as a high deposition process in the past. New torch technology as well as modern power sources are the reason for this. The plasma-MIG process is a standard MIG process with a concentric plasma torch around it. Both processes are controlled by separate power sources. As the plasma process stabilises the MIG-process and vice versa, parameters for both of them can be varied in a wide range. Thus possible applications reach from high deposition aluminium and steel welding, making use from the wire preheating and the extra heat input from the plasma process to highly stable medium deposition processes with the extra benefit, that the additional plasma cleans the surface directly before material is deposited with benefits in aluminium welding down to plasma-MIG brazing with very low heat inputs and the possibility of influencing bead shape.

2.2. Developments in Beam-Welding Processes

2.2.1. Electron Beam Welding

The range of joining tasks for electron beam welding reaches from foil welding with plate thickness of just a few 1/10 mm up to thick plate welding with achievable weld depths of 150 mm. Moreover, almost all electrically conductive materials are weldable, many of those materials may also be joined in material combinations. The high power density in the range from up to 108 W/cm^2 which is typical of electron beam welding and the connected dept-to-width ratio of the weld (up to 50:1) allows a large variety of possible applications of this joining process.

Standard electron beam welding is normally carried out in a vacuum chamber under high-or low-vacuum, but there is also the possibility to use the electron beam in a free atmosphere.

In automotive industry, electron-beam welding in vacuum is mainly used for engine and gear parts. The NV-EBW method is mainly used for the joining of plates; filler material is frequently applied and allows high gap bridging abilities.

Non Vacuum-Electron Beam Welding

As in electron beam welding in free atmosphere (Non-Vacuum Electron Beam Welding; NV-EBW) a vacuum chamber is not necessary and thus evacuation times as well as chamber-conditioned restrictions to the component dimensions may be set aside, this method is most advantageous. The technique has been developed in Germany in the Sixties. The beam generators are of the same design as those in vacuum-EBW. Figure 5 shows a NV-EBW generator and a typical application.

The half-shells of the depicted aluminium hollow-sections are joined by the non-vacuum electron beam welding method. Welding speeds of up to 12m/min are applied which makes NV-EBW also a highly profitable method. There are further reasons, besides the high welding speed, which make NV-EBW applications highly recommendable.

In comparison with laser beam welding methods which, for many applications, are directly competing with NV-EBW methods, the electron beam is able to penetrate the workpiece surface independently from angles or surfaces. After leaving the beam generator, the beam is guided into ranges of higher pressure right to atmospheric pressure. Series-connected chambers generate the drop of pressure. The beam is focused onto the exit nozzle which has a diameter of 1-2 mm. With rising ambient pressure the electron beam is scattered through a collision with gas molecules and enlarges. In free atmosphere the beam maintains its initial power density over a short length only. During welding, a maximum working distance of approx. 25 mm must not be exceeded.

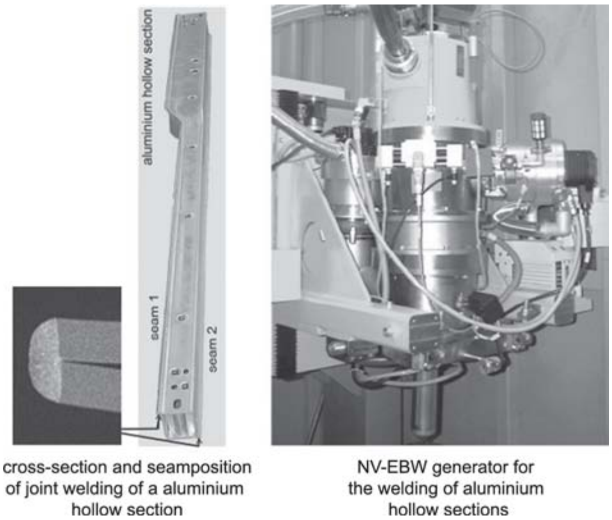

Figure 5. NV-EBW Gun and Aluminium Hollow - Section Welding, (Courtesy: Steigerwald)

The beam diameter is between 1,5 mm and 2,5 mm, depending on the working distance and the accelerating voltage. This focused spot which is, compared with vacuum-EBW and laser beam welding relatively large, allows a good gap bridging ability and a relatively coarse edge preparation in a combination with filler material

The utilisation of the energy density of the electron beam in free atmosphere and the high available machine powers allow to achieve weld speeds of 20 m/min with steel materials and more than 50 m/min with aluminium alloys.

2.2.2. Laser Beam Welding

Laser beam welds are characterised by a high depth-to-width ratio, resulting in a minimum influence on material properties and high welding speeds. On the other hand, the demands on seam preparation and positioning are high and gap bridging ability is low. Recent developments mainly focus on optimising gap bridging ability and welding time and to lower demands on seam preparation and positioning.

2.2.2.1. Laser Beam Welding with Filler-Wire

Adding a precise wire feeding device to the standard laser process is the simplest extension. By adding filler material, it is possible to fill gaps and take influence on the metallurgy of the weld. This qualifies laser beam welding with filler-wire also for material combinations with intermediate layers as well as for materials tending to crack.

Laser-MIG hybrid welding is the combination of a laser welding process and a standard GMA-Process in one common welding zone. It combines the deep penetration of the laser beam welding process with the good gap bridging ability of GMA welding. Furthermore, the laser process stabilises the GMA process. As filler material is applied as a liquid, high welding speeds can be achieved with low heat inputs. Applications for Laser-MIG hybrid welding are steel (CO_2-lasers) and lightweight alloys (Nd:YAG-Lasers), plates thickness start from car body sheets and are limited by the available laser power. A rule of thumb estimates 1 mm plate thickness per kW CO_2-laser power for steel. First industrial applications in automotive industry are in the production of aluminium car bodies, Figure 6.

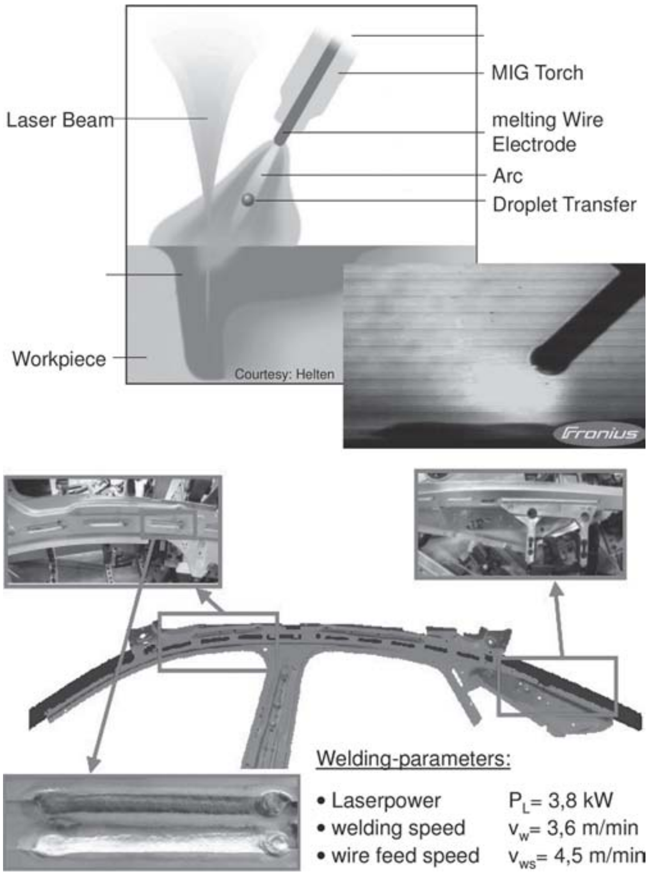

Figure 6. Laser-MIG-Hybrid welding of car roof structure, (Courtesy: Audi)

2.2.2.2. Remote Welding

When replacing spot welds by laser welds, this is usually done by short welds, that require long travel times between the welds when carried out with robot guided laser optics. To reduce these travel times, it is necessary to reduce the moved mass, only deflecting the Laser beam itself is the ideal case. The principle of remote welding shows, one or two mirrors deflect the laser beam, positioning the focus in height direction is done by moving the long focus focussing lens along the axis of the beam.

The realisation of remote welding was only possible with a new Laser generation with optimum beam Quality such as CO_2-Slab-Laser. Together with a focussing lens of 1600 mm, this opens a considerable working field, which may be enhanced by mounting the remote welding unit to a 3Drobot. With remote welding, the travel time between the welds may be reduced to a few 1/100 sec. reducing welding time by up to 25 %.

2.3. Spot welding

High strength steels, as they will be employed in the future generations of car bodies, require modifications of the existing spot welding technology. The main concern here lies in the use of special force/movement programs with higher forces, as they can be applied with present pneumatic or hydraulic welding equipment.

Resulting from this, new electro-mechanic welding devices are being developed, that are capable of applying the required higher welding forces. Their capabilities are currently evaluated.

3. "COLD" joining technologies

The combination of different material types, may they be steels, lightweight alloys or polymers, between each other require joining processes different from the classic thermal welding processes. Mechanical joining processes and adhesive bonding are gaining increasing importance with the increasing applications of these materials.

3.1. Mechanical Joining

Not only in multi-material constructions but also for the spotwise joining of aluminium clinching and punch riveting are applied in increasing numbers. Clinching does not require additional parts such as rivets to join plates. A disadvantage of this process is the low crash strength and its restriction to materials of lower strength grades. Punch riveting reaches strength levels comparable to spot welding. Typical for this variant is the use of an additional rivet, that cuts through the plates, Figure 7.

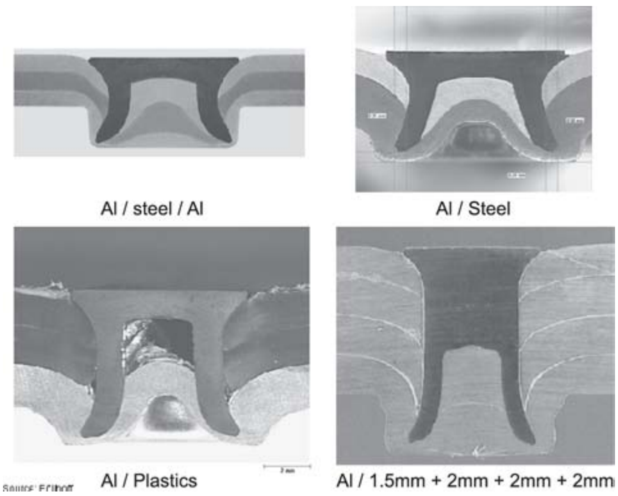

Figure 7. Punch Riveting

Advantages for both clinching and punch riveting are the low distortion and the ability of joining different materials. They can replace spotwelds in some cases.

3.2. Adhesive Bonding

Structural adhesive bonding is gaining importance in car body building for a few years now. Advantages are seen in the two-dimensional force transmission, resulting in better stiffness and crash properties of the joined structures. Adhesive Bonding is normally combined with other joining processes such as clinching, punch riveting or spot welding.

4. Simulation of joining techniques

The reduction of development time for new car models, the need of cost reduction and increasing safety demands in turn increase the necessity of sophisticated simulation tools. Simulation has become an important helper to learn about product properties, to optimise construction details and production processes, as well as to reduce development and product costs and enhance product quality.

A recourse is to simulate welding and joining processes through a set of mathematical equations representing the essential physical processes of welding. The activities of welding modelling proceed the following directions, associated with the different physical phenomena, which occur during welding with GMA, TIG, beam and spot welding processes:

- Heat source - metal interaction
- Heat and fluid flow
- Weld solidification microstructure
- Phase transformation / weld microstructure
- Residual stresses and distortions
- Mechanical properties and integrity
- Weld geometry

Several simulation programmes have been developed to compute one or more of the named outputs. Work is still in progress. Future ambitions result in linking the output of these simulation programs to design and calculation software and planning systems in order to get an overall virtual view of all aspects of automobile design, testing and production.

5. Commercial relevance of joining techniques

The recent study "Macroeconomical and sectoral creation of value from production and application of joining techniques" which, at the instigation of the German Welding Society (DVS), has been drawn up by the Hochschule Niederrhein, Mrs. Professor Moss, for the fair "Welding and Cutting" in 2005, shows the direct and also the indirect creation of value, gained from applications of joining technology.

In Germany, the direct creation of value through the application of joining techniques for devices, filler materials, gases, adhesives, occupational safety and professional training amounts to approx. 3,6 billion €. This amount has been calculated only conservatively since many joining methods are, statistically, hard to apply. Germany holds approximately one third of the European market share for joining technologies; Europe, on the other hand, holds approximately one third of the world market share - this means that from 3,6 billion € from Germany a value creation of approx. 11 billion € for Europe, and, worldwide, a value creation of 33 billion € can be extrapolated.

Since the joining technique is an interdisciplinary technology which is used within the range of the entire national economy it is important to realize the quantity of the value creation in the manufacturing sector using joining techniques. Following again conservative estimations, these are about 27 billion € in Germany which conforms to approximately 4,8 % of the total value creation by the German manufacturing industry.

Approximately 640.000 jobholders are, in Germany, working in the field of joining technologies; this conforms to approx. 6% of all jobholders in the manufacturing industry. Every 16th working place in the manufacturing industry is provided by the application of joining technologies.

6. Conclusion

Joining is an interdisciplinary, sophisticated and indispensable technology. Joining technique is a key technology and will, also in future, remain a key technology.

Joining technologies are interesting and fascinating and, despite many novel developments in recent years there is still a lot of work to be done in future.