TECHNICAL REPORT

Technology for sheet forming and joining of bipolar plates for PEM fuel cell applications

(Appendix 2 to BALBAS end-report)

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Initiator: Project **BALBAS**

Summary

This report summarizes technologies for forming and joining of metallic bipolar plates (BPP) for use in Proton exchange membrane fuel cells (PEMFC), with the perspective of using Aluminum as base material. The state-of-the-art technologies are noted, and alternative technologies are presented and discussed. The ambition is not to produce a document for peer review, publication or education, nor to present the state of the art of forming technology. It should include enough information to point the reader in the right direction, should interest for a certain technology arise.

It is noted that within forming there are many technologies that are actually used, and no single forming method has obtained a de-facto monopoly - they compete for their future on the market. Different variants of mechanical stamping processes and hydroforming are used in practice today, and there are alternatives that could be used after further development and/or adaptation.

Within the field of BPP joining, there seems to be a clear go-to method that has reached at least a near-monopoly on the market and it is laser welding. Here, this technology is to some extent compared with alternative technologies that potentially could be employed after varying degrees of development and adaptation.

1 Contents

2 Background

2.1 General introduction

There is rapid development today to establish, produce and implement technology that helps eliminate greenhouse gas emissions. Recent events in eastern Europe, the Russian invasion of the Ukraine, has motivated western Europe to liberate itself from Russian oil, coal, and gas at an increased speed. This extends to a generally faster decoupling from fossil fuel sources.

Power generation and vehicle propulsion, when fueled by hydrocarbons, are significant sources of emissions that drive a large part of technology development. Emission free energy generation i.e. solar PV parks, household PV systems, wind power (on and offshore), are part of the outcome of such development, and are viewed as standard technology today, with increasing numbers of installations around the planet.

Some of the energy generated by these sources is used to propel battery electric vehicles (BEV), which are increasing in numbers at a pace that few expected some years ago. The quantity of emissions generated by BEV does not come primarily from the vehicle itself but by way the electricity used to charge the batteries was generated. To minimize emissions, the sourced electricity must be green, i.e. solar, wind, geothermal or hydro. Besides emissions generated by driving the vehicle, the production of the vehicle itself generates emissions. Several automotive OEMs have expressed strong dedication to eliminating the CO_2 emissions generated by vehicle production (Polestar, Scania, other).

It would be wrong to assume that one technology will be the winner, and the future standard. In reality, a variety of technologies that satisfy different user requirements will most likely be needed.

Fuel cells represent a family of technologies that offer an alternative source of power to batteries in general. Proton Membrane Exchange (PEM) fuel cells in particular are used as a power source in several industries, including automotive. The PEM fuel cell contains a number of cells where hydrogen and oxygen are combined and produce electric energy, heat and water. The cell consists of an anode, a cathode and membrane electrode assembly (MEA). The cells are stacked and connected in series. The anode of one cell is connected to the cathode of the next cell. Together, the anode /cathode assembly constitutes the bipolar plate (BPP). The plates have channels for distribution of gas to the MEA.

Bipolar plates are made of a variety of materials. Graphite is a traditional material used in bipolar plates. It is found either in pure form or as a composite. Graphite is viewed as heavy, thick, and brittle, but has excellent electrical conducting properties, low electrical contact resistance and excellent corrosion resistance. Metal BPP are increasingly used to reduce weight and volume. Typical materials are stainless steel and titanium. Aluminium is often mentioned as a candidate metal. It must be coated for corrosion protection. There is little information in the literature concerning aluminium based BPPs. The information available is mostly the results of academic research. There is very little information regarding commercial use of aluminium BPP.

The channels in metal BPP can be formed by a number of methods, which are explored. These methods have pros and cons and vary in cost. Some methods involve removal of material for the channels while others involve plastic forming of the plate. Also, the question of forming prior to or after coating is of interest, as coating individual plates is deemed more costly than coating reel to reel.

Besides forming, bipolar plates consist of two plates which calls for a joining process which seals and provides electrical contact between the cells. Various methods are available, although some are more common than others. Laser welding is likely the most common method. Adhesive bonding is mentioned as a possible method.

2.2 Purpose and limitations

The purpose of this document is to present an orientation of available methods of creating channels on BPPs made of aluminium, and to some extent evaluate performance regarding cost, productivity, production volume and surface quality. Joining methods are also identified and evaluated to a certain extent.

- The ambition is not to produce a document for peer review, publication or education, nor to present the state of the art of forming technology. It should include enough information to point the reader in the right direction, should interest for a certain technology arise.

Aluminium offers a significant reduction in cost for the material, compared to stainless steel or titanium. The cost of surface coating is likely to be of approximately the same level for all metal BPP materials. The cost of forming is affected by sheet material strength and hardness, as it effects tool wear. BPP are likely to be produced in large numbers whereby tool and machine investment have impact on cost.

The quality of the information is highly dependent upon the source. Some information is available in, and retrieved from, the public space. Some comes from companies that deliver equipment for such production. The scope is limited to PEM fuel cells and aluminium sheet produced by rolling. The information is limited to that available in public space and commercial sources. There is no in-depth investigation into hypothetical technologies that are in early development.

2.3 PEM Fuel cells and bipolar plates

Polymer electrolyte (or proton exchange) membrane (PEM) fuel cell, in simple terms, consists of an anode, a polymer electrolyte membrane and a cathode, see Figure 1. To increase voltage, a number of cells are stacked together, see Figure 2. A fuel cell stack in an automotive application may consist of 300-500 cells. The anode of one cell is connected to the cathode of the next cell. In practice, such a component constitutes the bipolar plate.

A metal bipolar plate is an assembly consisting of two formed metal sheets joined together and with gaskets mounted on each side, see Figure 3. The sheets typically have different flow patterns. The anode, where hydrogen is supplied, may have a fine, zig zag pattern to increase exposure to the GDL. The cathode may have a slightly larger pattern with straight channels for air exposure. In between the plates there are channels where coolant flows to control the temperature in the stack. The sheets also have holes where hydrogen and oxygen are fed into the system.

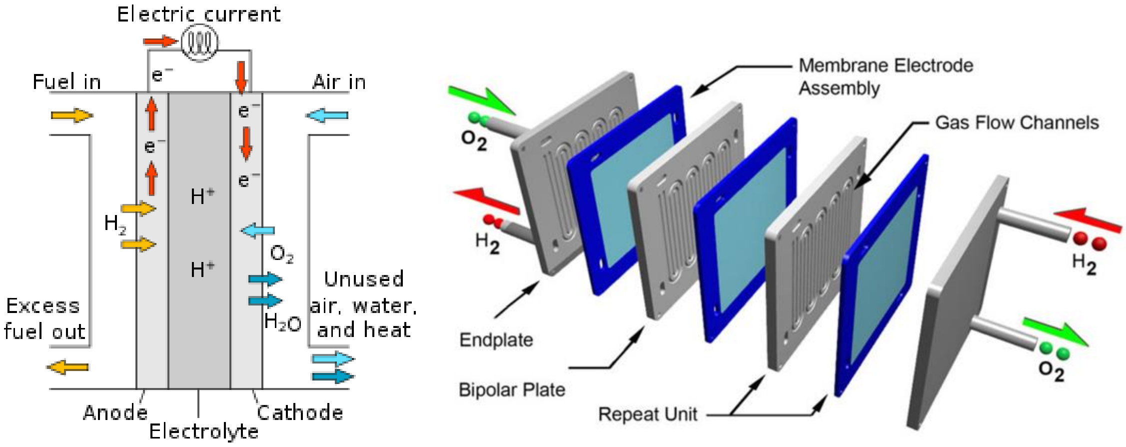


Figure 1 Principle for PEM fuel cell [1] and fuel cell stack [2].

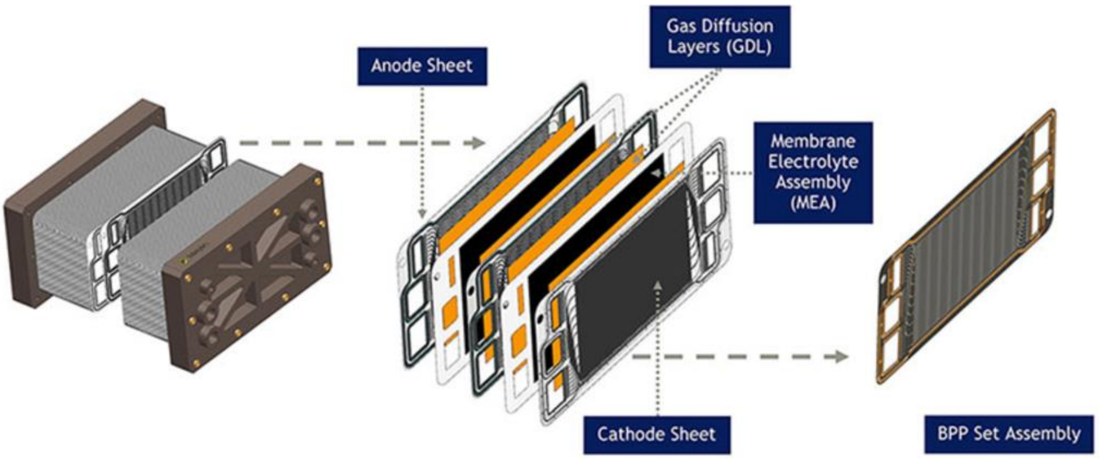


Figure 2 Bipolar plates in a PEM fuel cell stack assembly [3].

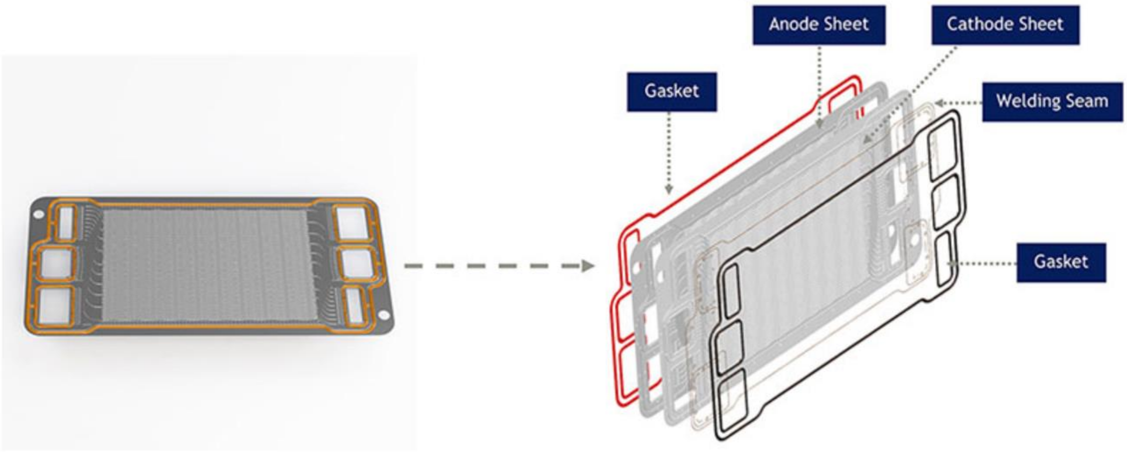


Figure 3 Bipolar plate assembly [4].

The internal environment of the MEA is notably acidic, typically PH2 or lower, but the hydrophobic GDLs creates a distance to the cell reaction and therefore the corrosion potential at the BPP is decoupled and more dependent on the local conditions of the BPP/GDL interface. At the same time, the contact between the bipolar plate and the gas diffusion layer of the electrolyte membrane assembly must have low conductive resistance in order to convey electric current.

3 Forming technologies

3.1 Background

The US Department of Energy has several model cases for fuel cell vehicles [5-7]. One scenario consists of 500,000 vehicles per year. The model vehicle has 80kW power. The fuel stack consists of 760 plates amounting to a total of 380 M bipolar plates per year. This is a significant and challenging volume of plates. There are currently only a handful of companies in the world capable of supplying such products at this volume and quality.

At HYF-cell 2022, several machine suppliers, such as Cellform, offered production lines for bipolar plates. These had a capacity of 2-5 M plates per year, which would correspond to ~2600 – ~13200 vehicles per year. Graebener, a producer and supplier of equipment for hydroforming bipolar plates, presented a production line capable of up to 5 M plates/year. Such a line would include forming, trim, laser welding and gasket installation. Production speed is another KPI used to describe production capacity. Cellform, a German company that supplies bipolar plates manufactured by progressive stamping, targets a production speed of 1 plate/s. Cell Impact, a Swedish BPP producer, utilizes a unique stamping technology, adiabatic forming, with a production speed of 2 plates/s or higher.

3.2 Set up for forming

A production line for bipolar plates typically has a clear material flow, see Figure 4. This is affected by the available footprint of the building, the processes involved and the number of machines in total needed for handling and each process step.

From a handling point of view, the longer in the process that the material remains on coil, the lower the costs will typically be. That means material is first subject to surface treatment and then forming, joining, gasket application and quality control. Several suppliers of complete BPP, for installation in fuel cells, claim that forming is possible after surface treatment, which enables surface treatment on coil, or roll to roll. Some of these suppliers work with hard tools in a more or less standard stamping procedure. Surface strain on the sheet, due to abrasion or strain in the sheet, may cause the surface coating to crack, thus exposing the underlying material to the harsh environment in the fuel cell.

The other alternative is starting with precut blanks that first undergo the forming process then the coating process. The potentially harsh forming process is done prior to coating thus potentially eliminating the risk of cracks in the coating.

A production line for BPP will include some or all of the following: material handling for incoming material, cutting (blanking), forming, coating, joining, gasket application, quality control, packing.

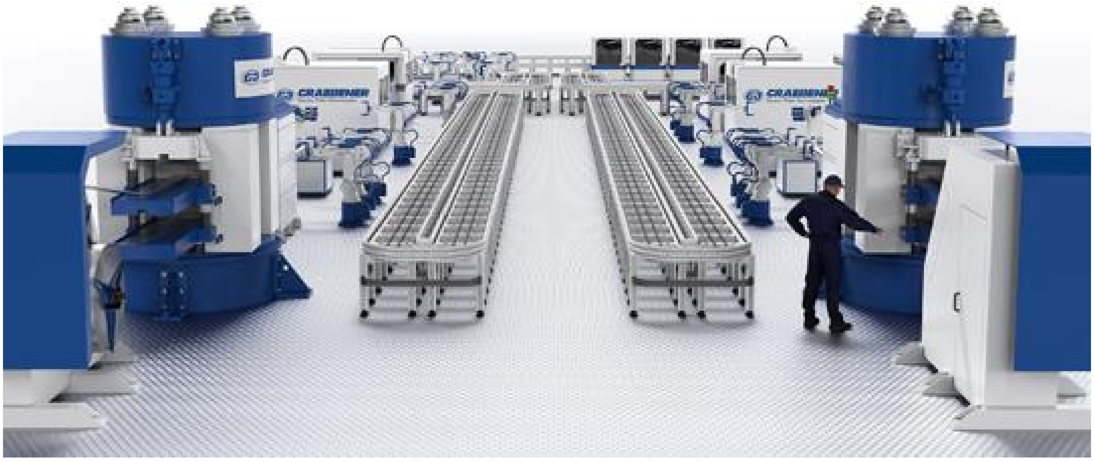


Figure 4 Two parallel production lines for bipolar plates [8].

3.3 Stamping

In simple terms, traditional stamping is a process where sheet material (on roll or as blank) is formed in a tool, typically consisting of a punch and die. The tooling is typically made of hard and strong tool steel grades. In some cases, a hard die is used together with a soft punch made of rubber. This is a bit more economic than using a hard punch. Hard tools for BPP are produced by milling and polishing. Tools are often quite costly and impact the price for the BPP. In analysis by Strategic Analysis [9], the tooling cost is estimated at 8% of the BPP cost at high volume (500k vehicles per year). The production set up in that document includes progressive stamping.

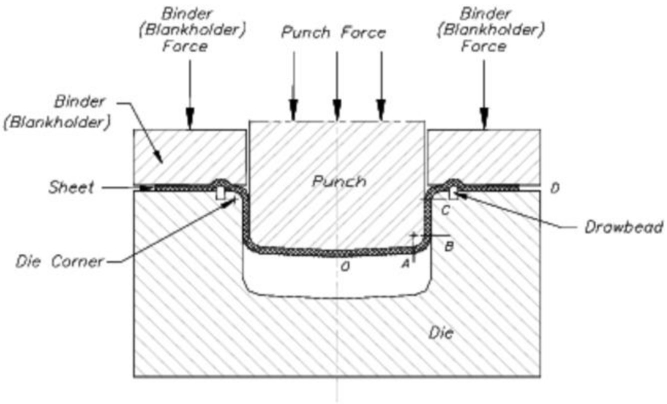


Figure 5 Principle of metal sheet stamping [10].

The stamping operation is typically executed in a press that closes and opens the tool. A mechanical stamping press is often used for smaller parts with shallow forming. A hydraulic press is used for larger parts where high press force is needed for a longer depth. Infeed material could be metal coil or blanks. Stamping operations include forming, punching, coining, cutting, and bending. Stamping is a process suited for high volume production as production speeds can be high, in excess of 1500 parts per minute. The tools, although sensitive to damage if handled incorrectly, have long lifetime and last for long production runs.

Press forces needed for forming vary depending on the size of the part, material of the part, the amount of forming, and the dimensional tolerances. The press force also decides the type of press needed for the operation. Small parts with simple forming may call for a mechanical press with fairly low force, but capable of producing hundreds of parts a minute. Large complex parts may call for a large hydraulic press (>10kN) capable of <50 parts per minute.

Local thinning is an issue that must be addressed in the forming process, Figure 6. The material at the top and bottom of the section is locked in by friction against the tooling, prohibiting material flow. The following strains are allocated to the areas close to the corners, and not the entire section, thus distributing strains over a short length. The consequence being failure in the sheet, see Figure 7.

Cellform [11] and Feintool [12] produce BPP by stamping and both have stated (at F-cell show in Stuttgart) that they produce BPP without (or with negligible) local thinning. Neither would go into details, stating that their technologies were proprietary.

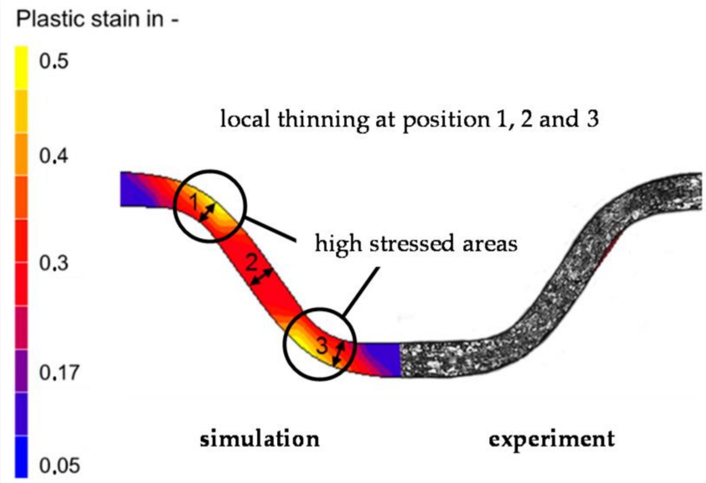


Figure 6 Local thinning typically takes place in the corners of the cross section of a bipolar plate [13].

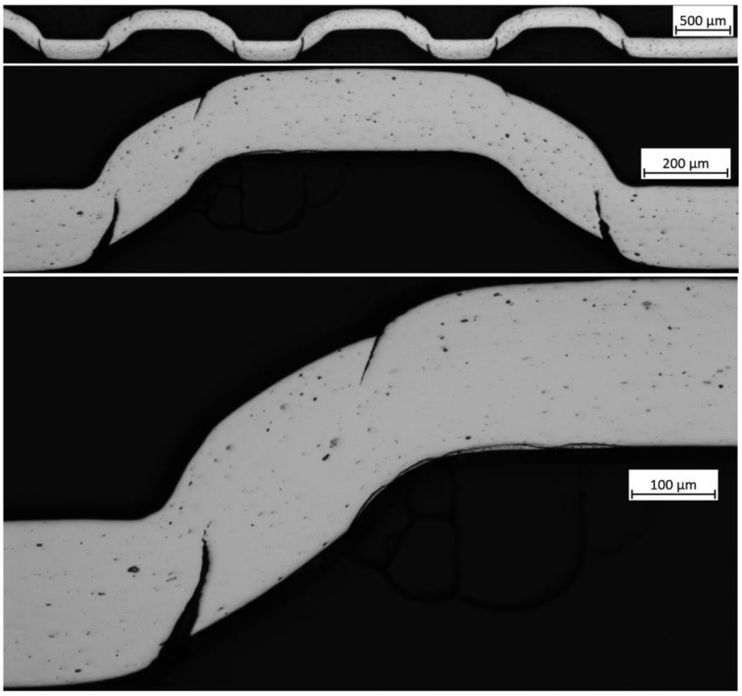


Figure 7 Failure of low ductility AA5xxx sheet during forming process. Tearing occurs in the corner areas where strains are large (Gränges internal image).

3.3.1 Rubber pad forming

There are hybrid types of stamping. One such method is rubber pad forming where the die consists of a rubber pad instead of a hard tool [14], see Figure 8.

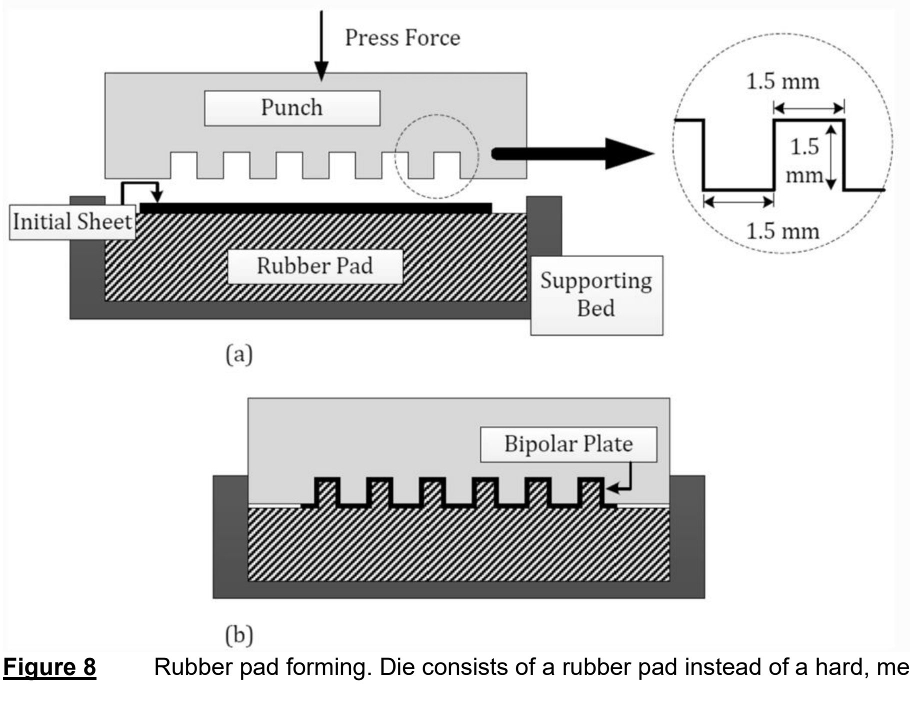


Figure 8 Rubber pad forming. Die consists of a rubber pad instead of a hard, metal die.

3.3.2 Progressive Die Stamping

Progressive die stamping is a process that includes two or more stamping steps in line. The steps include forming, punching, coining or other things. The workpiece is moved through a reciprocating stamping press from one process step to the next, for each press cycle. The parts in progress stay connected to the strip until the final step, where the finished part is dislocated from the strip. The residual material is scrapped. The overarching principles are shown in Figures 9 and 10.

Progressive stamping can also be produced on transfer presses. Here, the discreet workpiece is transferred from one forming station to the next, for each press cycle, often by means of linear handling equipment or articulated robots. This setup often includes a number of individual presses. Pre-cut blanks are often used as infeed in transfer presses which may reduce the amount of scrap in the process. This technology enables relatively high productivity for complex parts at a relatively low cycle speed. This setup calls for more complex tooling including a number of tools which affects tooling costs. Progressive stamping enables forming in several steps which allows for material movement in the workpiece under forming, thus avoiding thinning in areas under tension. Forming may produce high strains in the sheet whereas lateral movement lowers tensile stress and strain.

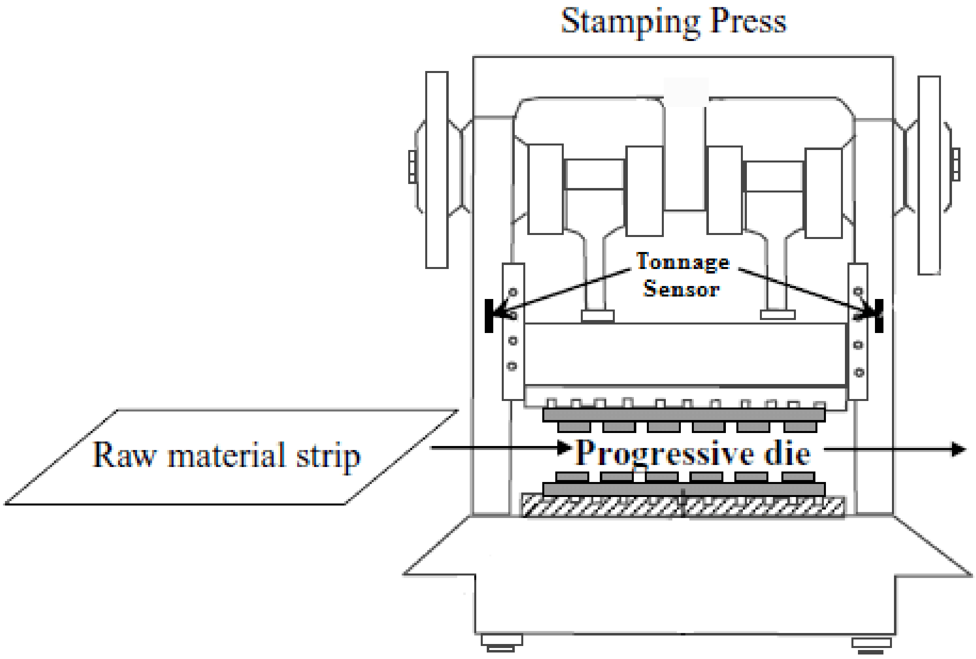


Figure 9 Principle for progressive stamping process. Raw material is fed into the progressive die. For each stamping movement, the material is moved one step to the right. After a number of stamping movements and transfers, finished parts exit at right [15].

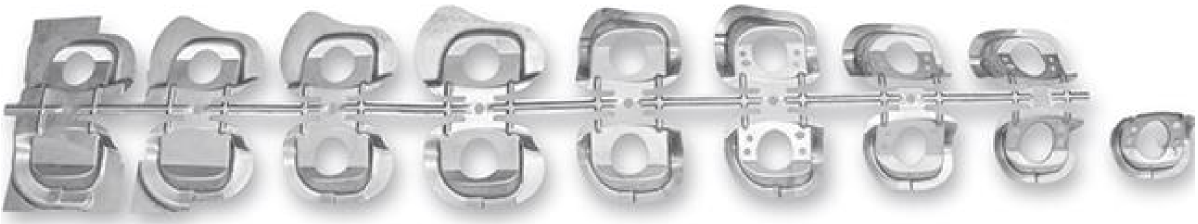


Figure 10 Parts produced by progressive stamping. From the left, each pair represents a stamping step in the process, with parts connected to strip [16].

3.3.3 Punching, cutting, notching

The production of BPP includes punching holes and trimming edges. For the sake of efficiency and quality, it is often integrated into the stamping process. Punching and cutting functions are built into the stamping tools which increases the level of complexity and cost. There is also the need for evacuation of scrap in the process. This is also a function built into the tooling. Scrap must be efficiently removed without exception. Should a piece of scrap end up in the forming area there is a significant risk of the tool being damaged which results in reparation and downtime costs.

3.4 Stamping equipment

3.4.1 Mechanical presses

Mechanical presses typically have the highest speeds. Mechanical presses come in various sizes and shapes. Several varieties are shown in Figures 11-13 [17-19]. The eccentric press is a workhorse in the stamping industry. Alternative solutions include C-frames and pillar frame. An eccentric press produces force through an electric motor, a flywheel with clutch and brake, and an eccentric shaft. The motor rotates the flywheel, where kinetic energy is stored. The shaft is connected to the flywheel through the clutch and brake. A stamping cycle is the 360° rotation of the flywheel where the energy it transferred through the shaft to the ram and into the part. The energy stored in the flywheel is thereby used for the stamping process. The highest force is at the bottom of the stroke.

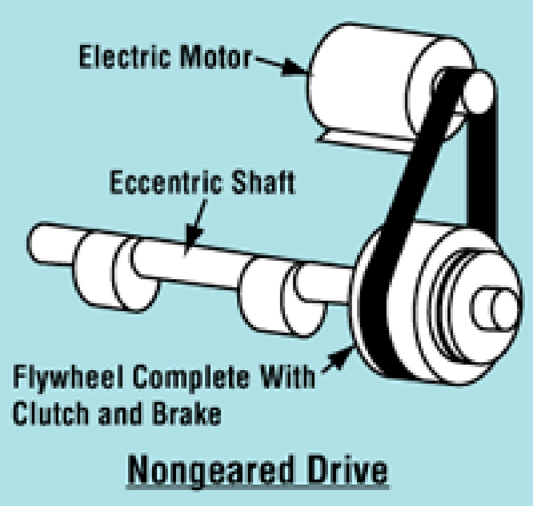


Figure 11 Schematic illustration of eccentric press.

Figure 12 Mechanical eccentric press (left) and C-frame mechanical press (right).

To summarize, mechanical presses have the following pros and cons:

Pros:

- Relatively inexpensive
- Fastest production
- High accuracy
- High repeatability
- Simple set up
- Available special slide motions
- Variable slide velocity
- Energy efficient
- Fixed stroke length

Cons:

- Limited versatility with variable stroke length, die space and pressure
- Lack flexibility

In hydraulic presses the ram force is derived through hydraulic pressure. The full press force is applied throughout the entire stroke as opposed to mechanical presses that achieve full force at the bottom of the stroke. Hydraulic presses are typically not as fast as mechanical presses. Leading producers of hydraulic presses include Schuler, AIDA, SMS Meer, Macrodyne, DEES, AP&T – see Figure 13, and others.

Figure 13 Hydraulic stamping press. Hydraulic cylinder on top of die holder.

Hydraulic presses have the following selected pros and cons:

Pros:
- Full tonnage throughout the stroke
- Unlimited customization and flexibility
- Longer tool life
- Variable stroke length
- Variable slide velocity
- Full working energy at any speed.

Cons:
- Slowest type of press
- Lower accuracy and repeatability

3.4.2 Mechanical servo presses

The mechanical servo press offers a bit of the best of both worlds [20, 21]. It enables complex steering of processing speed, position and pressure by numerical values, through the adoption of CNC and servo motors. This, in turn, opens the possibility of forming challenging materials such as aluminium, titanium, magnesium, high strength steel plate and carbon fiber composites which are increasingly used in automotive and other industries.

Stamping offers an unlimited variety of set ups for production of bipolar plates. The choice of equipment and set up is decided by BPP design, tolerances, materials, and most important production volumes. Press manufacturers promote servo presses for high volume BPP production. Which types of presses that are actually used in production today is difficult to assess. Stamping is used today for producing BPP and will be around for some time to come. But increasing volumes and the drive to reduce cost will most likely lead to the development and use of other methods.

Pros:

- High accuracy and repeatability.
- Full press capacity near the bottom dead center of stroke.
- Variable stroke profiles.
- Reduced tool wear.
- Precise slide motion and position control throughout the range of the stroke length.
- Variable, precise slide velocity control, even within a single cycle of the press stroke.

Cons:

- High initial cost

3.5 Chemical etching

Chemical etching is a subtractive manufacturing process where material is removed by the use of chemicals. It is an established process used for various products i.e. electrical components, medical devices, meshes, automotive interior trim and many others. It is an efficient process used on a most types of metals and alloys including steel, stainless steel, nickel, copper, titanium, aluminium and others. The process is illustrated in Figure 14 [22].

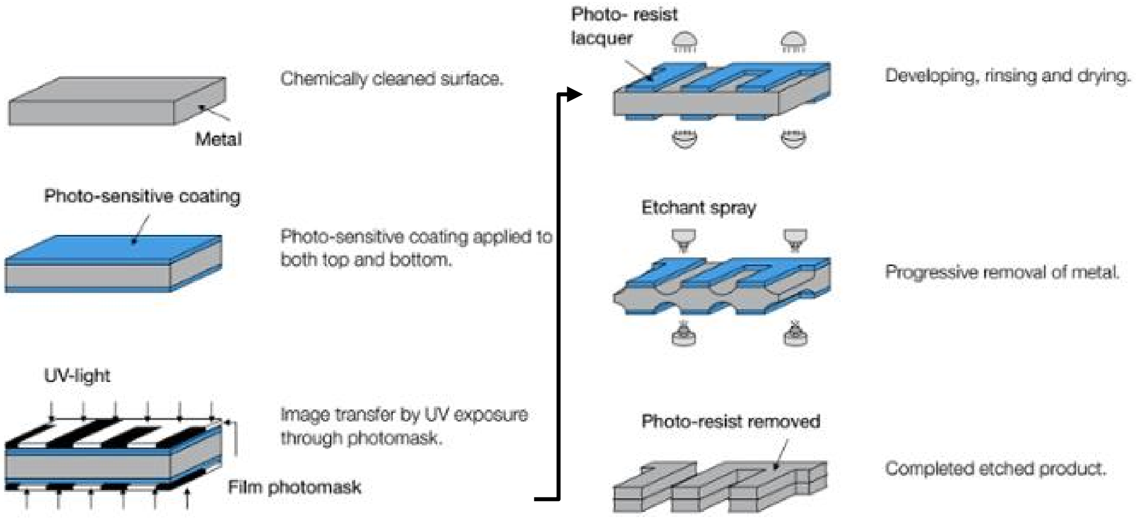


Figure 14 Process for chemical etching.

Chemical etching comes with a number of pros and cons, a selection of which follows:

Pros

- No residual stress (from forming) and burr free parts
- Micron sized features
- Tight tolerances
- Wide range of materials
- Substrate thickness range 25um to 2 mm
- Round holes, sharp edges, straight or profiled edges
- Rapid prototyping
- Cost effective manufacturing
- Flexible tooling

Cons:

- Large variable cost of resist and etching solution
- Cost of disposing used etching bath and etching sludge
- Channel depth depends on sheet thickness
- Channel form and aspect ratio difficult to customise

There may also be the possibility of performing chemical etching on material that is on coil. This in turn could open for surface treatment on coil after the etching process is done and topology finalized. The material would not be subject to plastic forming or abrasion after surface treatment, reducing the risk of damage to the coating.

The process set-up includes input coil handling, etching process and recoil equipment. Etching eliminates the need for forming tools which gives cost savings. There is no need for mechanically cleaning the sheet after etching to remove burrs. Prototyping is easy, fast and at a low cost. The lead time for prototypes is counted in days instead of weeks or months as is the case for stamping. Precision Micro, a leading supplier of chemical etching, with HQ situated in UK, describes the cost as *low* compared to *high* for stamping. A more detailed investigation would be of interest, but currently outside the scope of this document. BPP produced by chemical etching may still need forming, punching and trim steps depending on the geometry, which would call for processing.

3.6 Hydroforming

Hydroforming is a technology where a sheet is subject to high hydrostatic pressure on one side and formed into a die on the other side, see Figure 15. The hydrostatic pressure acts as a punch. Hydroforming is performed on sheet and tubes, with a difference in setup. It is also possible to include punching and trimming in the process.

As one surface is subject to hydraulic pressure, often a water-oil emulsion, only one side of the sheet is subject to contact with the hard tool. The surface of the water side is not subject to abrasion or friction against the tool surface. This in turn enables the forming of pre-coated sheet without damage to the coating.

Gräbener Maschinentechik [23] GmbH& Co.KG is a leading supplier of sheet hydroforming equipment. Borit [24] is another company specialized in hydroforming bipolar plates. Fluid Forming GmbH [25] is a German supplier of hydroforming equipment and products. The website mentions the capability of producing components for fuel cells. Schuler Group [26] is a supplier of hydroforming equipment, with long experience. PVI Hydroforming [27] is a Swedish hydroforming company that produces components by tube and sheet hydroforming.

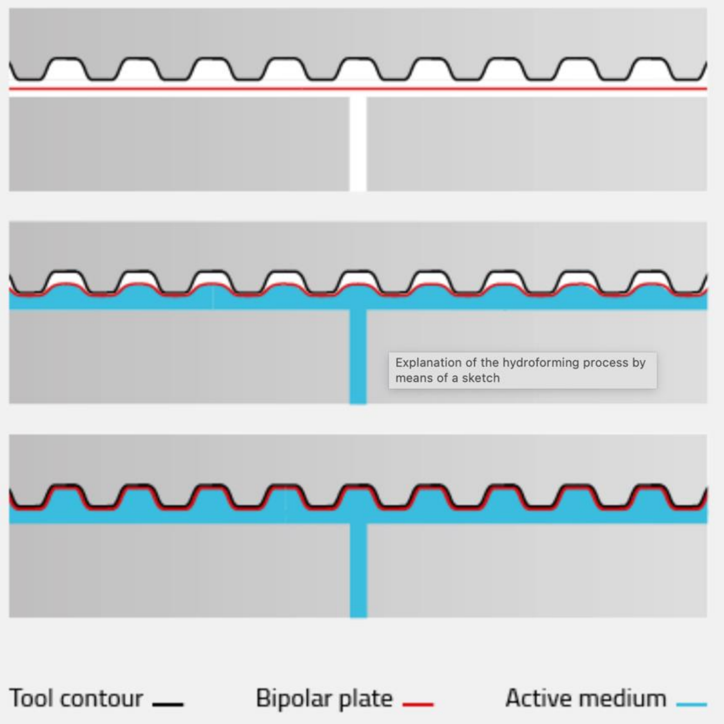


Figure 15 Sheet hydroforming where sheet is pressed into a die using hydrostatic pressure. The wet sheet surface does not make contact with a hard tool. The sheet coating is only affected by forming strains.

3.7 Adiabatic forming (softening)

Adiabatic forming, or softening, is a high speed technology where, simply speaking, the heat generated in the process is not dissipated to the surroundings until the forming is complete. The work piece is formed by tools impacting at high velocity, it is heated and softens during the process, and hardens again shortly after as it cools. This enables fast forming with high quality and shape stability. Cell Impact [28] is a Swedish company that supplies bipolar plates formed with this technology. They also sell equipment for adiabatic forming.

Pros:
- Fast cycle time
- Lubricant free process
- Low energy requirements
- Essentially no springback
- Work with very thin materials
- Improved formability
- Low capital expenditure
- Competitive product price

3.8 Electromagnetic pulse induced hydraulic forming

This is an interesting, fast forming technology that has been around for a while at research level but has recently been introduced to the market in an industrial form. The principle is that a hydraulic force, initiated and driven by an electromagnetic pulse, pushes the sheet into a die, as in the case of hydroforming, but at a speed of 50-200 m/s. This causes the workpiece to show viscoplastic behavior, which results in greater formability and absence of residual stress. Parts with more intricate details and smaller tolerances are possible to produce compared to stamping.

This technology enables forming of four or possibly more BPP (depending on size, in this case standard automotive size) in one pulse contributing to increased productivity. It is currently unknown if it is possible to include punching and trimming in the process. There are two companies that offer this technology; PST Products [29] in Germany and BMAX [30] in France.

3.9 Hot metal gas forming - HMGF

Hot metal gas forming is a similar process to, and further development of hydroforming. Instead of using fluid as a medium to create pressure and form the work piece against the die, hot gas is used. HMGF is a high volume production method that enables increased formability at lower pressures compared to hydroforming. Cost for tooling and machinery is an order of magnitude lower than that for hydroforming.

When applying hot gas forming on aluminium tubes, the workpiece and tools are heated to about or above 400°C. Cold gas is forced into the tube, whereby it gets heated the pressure increases. The gas then forces the workpiece against the die. At elevated temperatures, the workpiece has reduced strength and increased ductility.

If hot gas forming is to be applied one sided on sheet, the tool and material most likely must be heated to enable pressure build up and formability. There are few companies in Sweden that supply hot gas forming equipment. AP&T has supplied a test machine to Hydro Extrusions in Finspång.

3.10 Case study: hot/warm vs. cold forming

3.10.1 Formability study

The forming behavior of thin aluminum sheets was studied. Consequently, a test pattern was created, see Figure 16. The analyzed flow channel design is shown in Figure 17.

To benchmark the forming potential of thin aluminum sheets, four different sheet forming simulation models were built. The simulations were performed in AutoForm, employing three distinct materials: AA5182 O, AA3003 O, and 316L, all with a material thickness of 0.075mm. In addition to traditional cold forming, warm forming was simulated for the AA5182 O material. The forming operation was defined as crash forming. In Figure 18 the thinning results are presented. The thinning distribution appears different in all four simulations. During the warm forming of an AA5182-O sheet, a thinning of 26.2% occurs, which is also the highest thinning value among all four simulations. Cold forming of AA5182-O, when compared to SS316 (Stainless Steel), shows similar values. The simulated thickness distribution is presented in Figure 19.

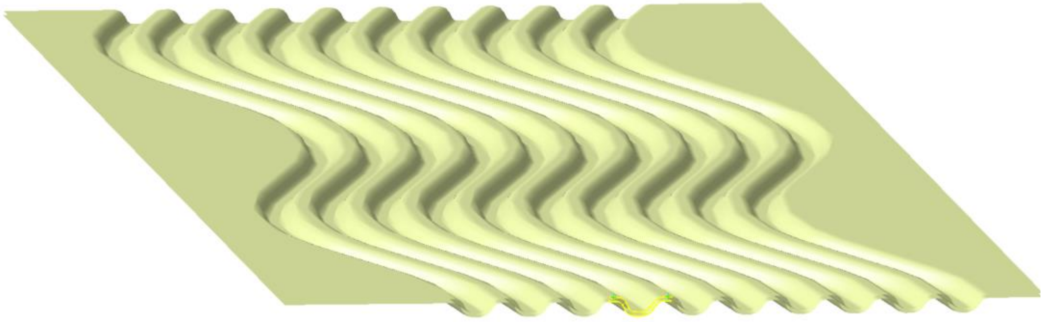


Figure 16 Demonstrator geometry

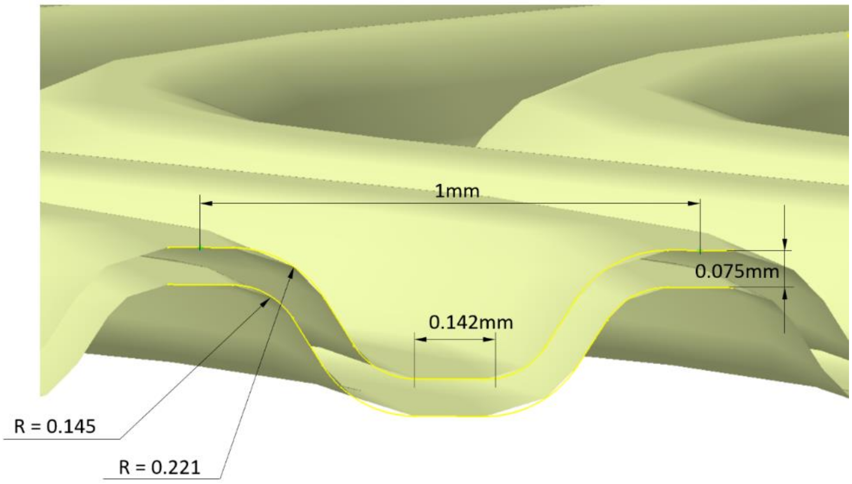
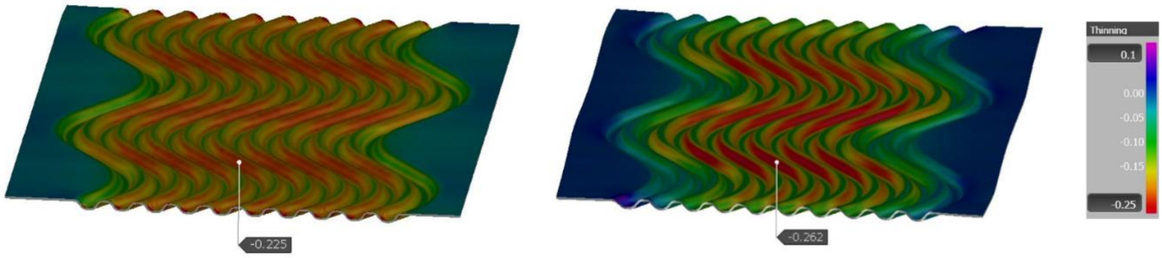
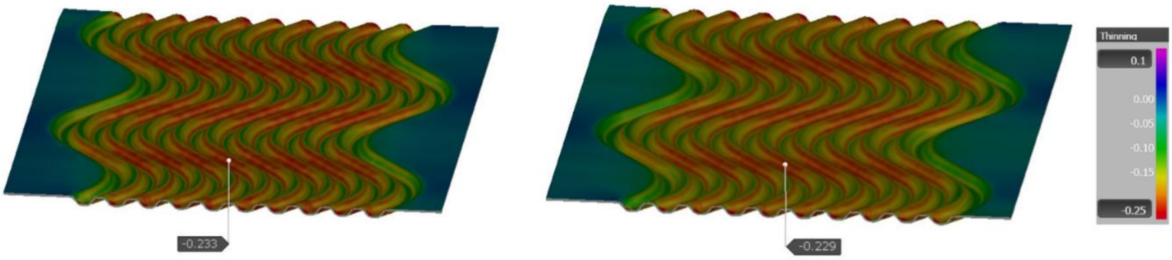


Figure 17 Demonstrator geometry – Channel profile



Thinning: AA5182 O – Cold Forming

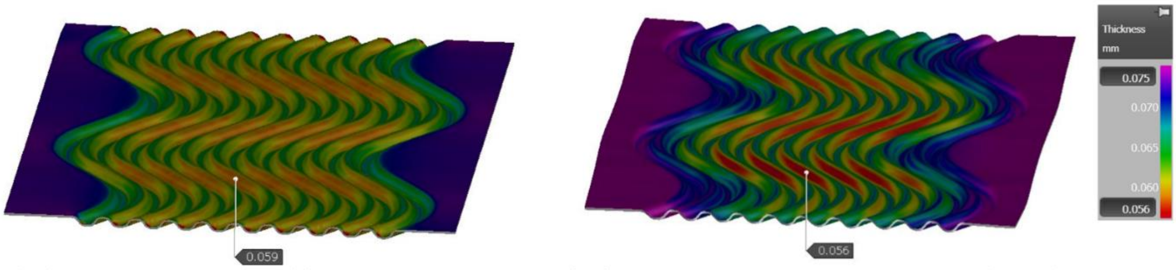
Thinning: AA5182 O – Warm Forming (200°C)



Thinning: AA3003 O – Cold Forming

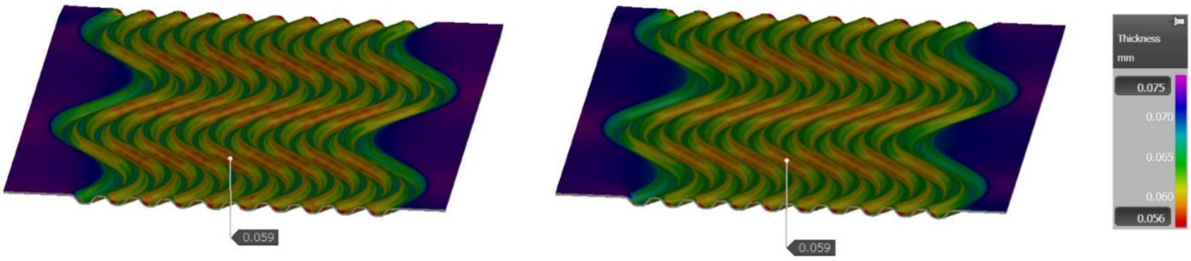
Thinning: SS316 – Cold Forming

Figure 18 Simulation results - Thinning



Thickening: AA5182 O – Cold Forming

Thickening: AA5182 O – Warm Forming (200°C)

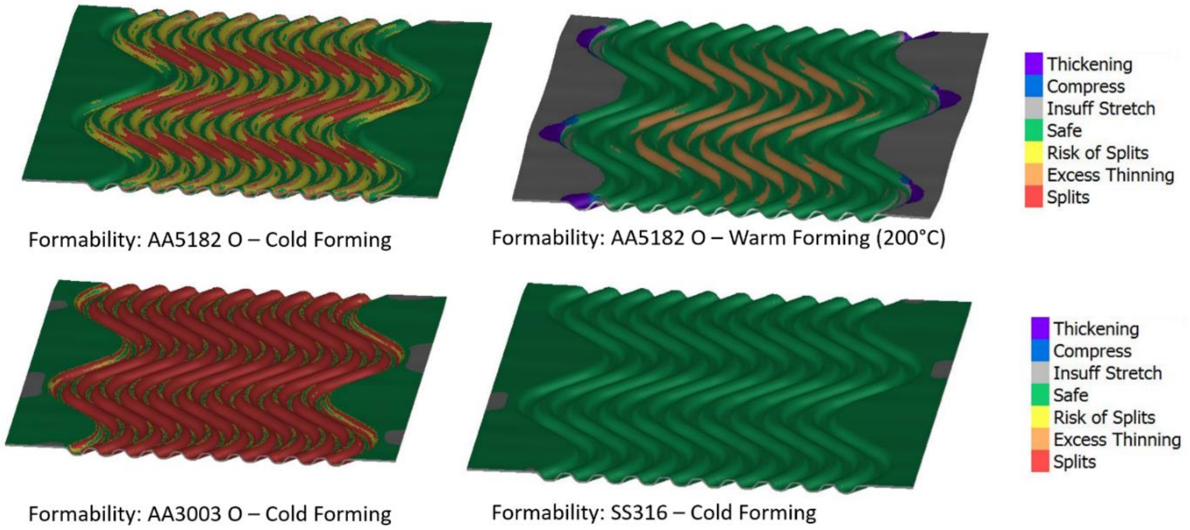


Thickening : AA3003 O – Cold Forming

Thickening: SS316 – Cold Forming

Figure 19 Simulation results - Thickness

Since the simulation results for thinning and sheet thickness do not provide information about material failure, the forming limit curve (FLC) was utilized in this study to analyze material failure. In Figure 20 the simulated formability results are shown, and it can be clearly seen that AA5182 O, when formed at 200°C, increases drawability, allowing for more strain before necking starts compared to a cold-formed AA5182 O material. Even though the thinning is higher when forming at 200°C, the material does not fail.


Formability: AA5182 O – Cold Forming

Formability: AA5182 O – Warm Forming (200°C)

Formability: AA3003 O – Cold Forming

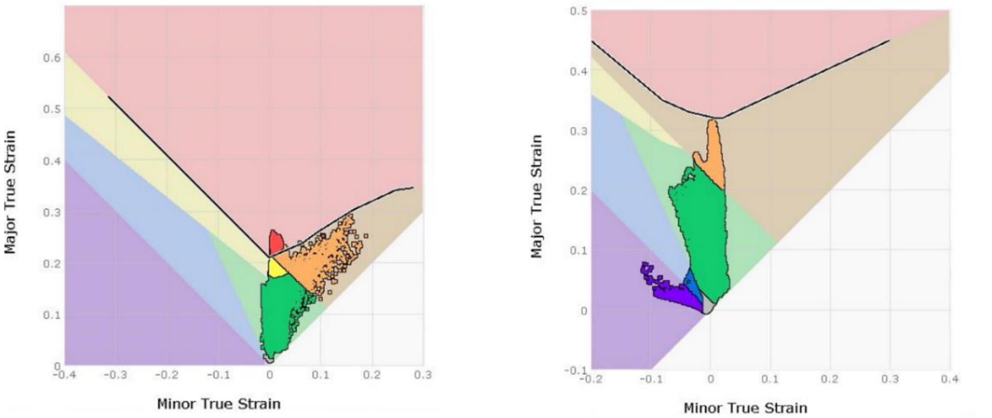
Formability: SS316 – Cold Forming

Figure 20 Simulation results - Formability

Upon evaluating the forming limit diagrams (FLD), it can be observed that the cold-formed AA3003 alloy in the O temper exceeds the FLC the most. Despite the thinning being similar to that of AA5182 in the O temper, the material is prone to cracking or failing at an earlier stage in the forming process, see Figure 21.

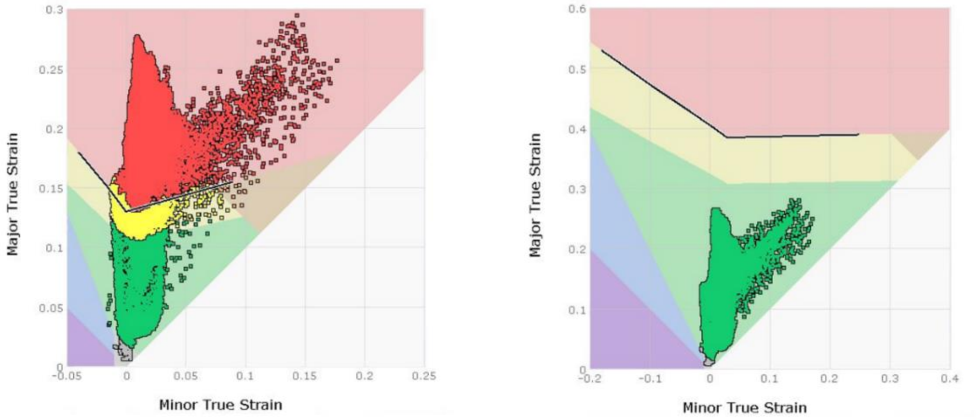
When comparing the AA5182 in the O temper, both cold-formed and at 200 °C, it can be seen that the higher FLC (for 200°C) indicates a possibility of a feasible component. Not only is the FLC shifted to a higher level, but also the major and minor strain distribution deviate between the cold and warm formed components. Higher plane strain values are achieved with warm forming, while on the other hand, stretch forming decreases.

Upon evaluating the 316L material, it is evident that the component exhibits only areas in the safe zone. There is still a small safety margin to the FLD, which indicates a low risk of forming the material with the studied geometry.



FLD: AA5182 O – Cold Forming

FLD: AA5182 O – Warm Forming (200°C)



FLD: AA3003 O – Cold Forming

FLD: SS316 – Cold Forming

Figure 21 Simulation results – Forming Limit Diagram (FLD).

3.10.2 Cost study

In the following section, the costs for coil cutting, stamping the pattern, and punching holes into the fuel cell plate were analyzed. Investment costs for the cutting and stamping line, as well as for the required tooling, were rough estimates, as the development of this type of equipment is still in its early stages. The assumption for equipment costs were based on AP&T's knowledge of similar machinery. Two investment scenarios were studied to analyze the impact of the investment value on part costs. Furthermore, a bipolar plate with an area of 20,000 mm^2 and a thickness of 0.075 mm was used. It was calculated with a cycle time of 30 strokes per minute, this leads to 9,720,000 strokes per year. A batch size of 15,000 strokes, 2 operators, and electric energy costs of 0.13 Euro/kWh were used in the calculation. Tables 1 and 2 list the main input parameters. For instance, material costs of 3 Euro/kg for an AA5182 in O temper and 4.5 Euro/kg for stainless steel 316L.

Table 1 Main Parameters used in the cost study / Investment scenario 1.

Forming Method	Material	Thickness	Investments scenario 1 Forming Line and Tooling	Raw Material Costs
Cold	AA5182-O	0,075mm	4.000.000 EURO	3 Euro/Kg
Warm (200°C)	AA5182-O	0,075mm	4.500.000 EURO	3 Euro/Kg
Cold	316L	0,075mm	4.000.000 EURO	4,5 Euro/Kg

Table 2 shows the cost per formed part depending on the number of cavities. AA5182 in O temper was compared to the stainless-steel material 316L. Furthermore, warm forming of aluminium and cold stamping was compared as a manufacturing method. In Table 1 and 2 investment scenario 1 is considered and Tables 3 and 4 list investment scenario 2.

Table 2 Cost per part depending on number of cavities / Investment scenarios 1

Forming Method	Material	Strokes per minute	Parts out per stroke (number of cavities)	Costs per formed part
Cold	AA5182-O	30	1	0,15215 Euro
Warm (200°C)	AA5182-O	30	1	0,16215 Euro
Cold	316L	30	1	0,193865 Euro
Cold	AA5182-O	30	2	0,08215 Euro
Warm (200°C)	AA5182-O	30	2	0,08715 Euro
Cold	316L	30	2	0,123865 Euro

Table 3 Main Parameters used in the cost study / Investment scenarios 2.

Forming Method	Material	Thickness	Investments scenario 2 Forming Line and Tooling	Raw Material Costs
Cold	AA5182-O	75µm	5.000.000 EURO	3 Euro/Kg
Warm (200°C)	AA5182-O	75µm	5.500.000 EURO	3 Euro/Kg
Cold	316L	75µm	5.000.000 EURO	4,5 Euro/Kg

Table 4 Cost per part depending on number of cavities / Investment scenarios 2.

Forming Method	Material	Strokes per minute	Parts out per stroke (number of cavities)	Costs per formed part
Cold	AA5182-O	30	1	0,17222 Euro
Warm (200°C)	AA5182-O	30	1	0,18370 Euro
Cold	316L	30	1	0,21393 Euro
Cold	AA5182-O	30	2	0,09218 Euro
Warm (200°C)	AA5182-O	30	2	0,09792 Euro
Cold	316L	30	2	0,13390 Euro

Figure 22 visualizes and compares production costs and raw material costs for warm forming (aluminum) and cold forming (stainless steel) in a graph. In the executed study, warm forming of an AA5182 alloy achieved a cost reduction of 16% (investment scenario 1) and 14% (investment scenario 2) compared to cold forming of stainless steel 316L. The results shown in Figure 22 are based on an output of 1 part per stroke (1 cavity). The reduction in costs can be explained by the lower weight of aluminum and the assumption of lower material costs compared to stainless steel.

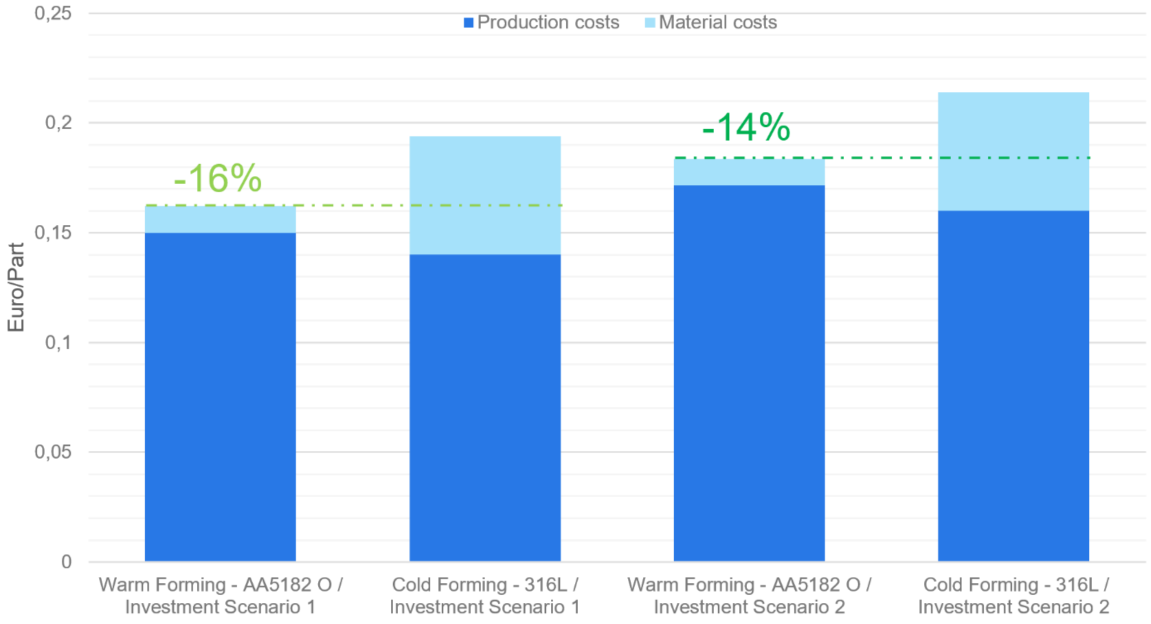


Figure 22 Costs per part – 1 part out per stroke

Figure 23 visualizes and compares production costs and raw material costs for warm forming (aluminum) and cold forming (stainless steel) in a graph based on an output of 2 parts per stroke (2 cavities). When using 2 cavities, warm forming of an AA5182 alloy achieved a cost reduction of 30% (investment scenario 1) and 27% (investment scenario 2) compared to cold forming of stainless steel 316L. Compared to the calculation with only 1 cavity, more costs can be saved. A higher output reduces the production costs, and thus, the lower material costs have a greater impact on the total costs of the part.

The production method of cold forming on AA5182 O would slightly result in lower costs compared to when warm forming is applied (Tables 2 and 4). However, due to the low formability of aluminium sheet materials, forming at elevated temperatures is considered to enhance formability and therefore prioritized and presented in Figures 22 and 23.

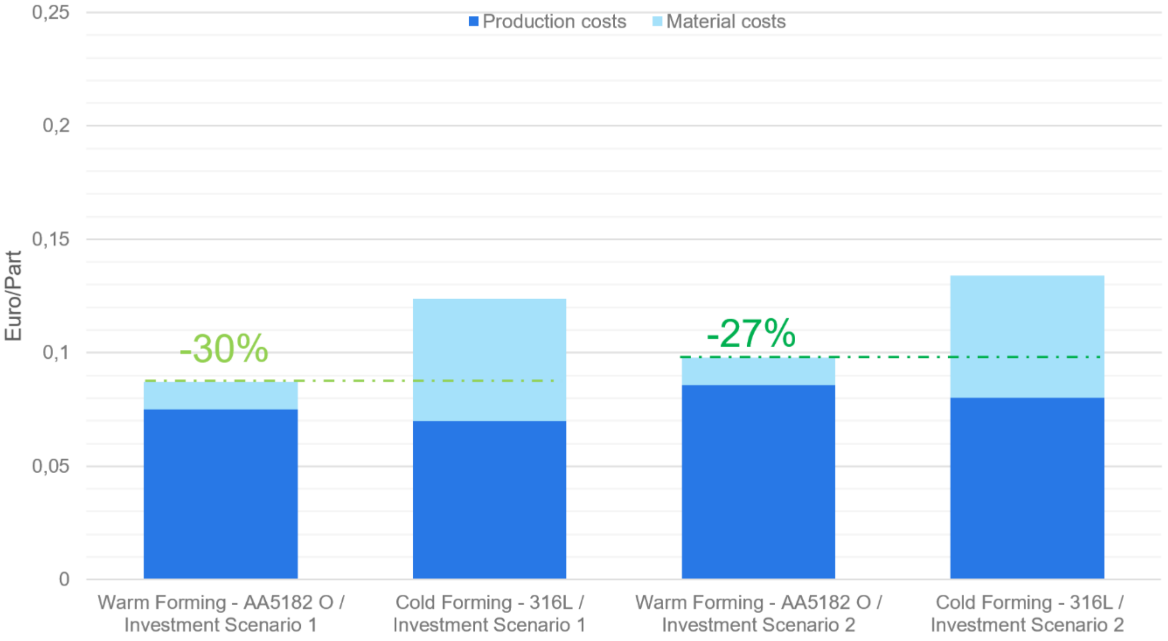


Figure 23 Costs per part – 2 parts out per stroke.

3.11 Coating prior to or after forming

There are several benefits and limitations to coil coating rather than coating of formed components.

It is normally economically advantageous to retain material in coil form for as long as possible in the production process or value chain. This is because it is so much easier and economical to handle one heavy piece of material than many small, light ones. Also, the risk of handling damage of a vast multitude of individual components is larger than one big coil of material. Finally, transportation of one big compact coiled material weighing many tons is more costly and cumbersome than transportation of hundreds of thousands of individually packaged plates. There are likely more advantages, the above should be seen as a brief selection.

Among the limitations it is important to realise that the coating needs to be whole on all locations that are exposed to corrosive substances. Thus, a coating that is cracked on these areas will not protect the aluminium. A coated coil is coated all over the surface. This means that the scrap falling from the production also contains the coating material, and it thus affects the recycling of the material. One can safely postulate that any coating material will downgrade the material and impair the recyclability, which will pose larger demands on melt treatment and reduce the value of the scrap. There are likely more limitations, the above should be seen as a brief selection.

4 Joining Technologies for metal BPP

4.1 General requirements on joints, and joining technology

Bipolar plates consist of two plates that are metallurgically joined together. On the inside, coolant flows to cool the joined plate pair and the MEA which is in mechanical contact with it. No matter which technology is used to join the plates they need to satisfy a set of basic requirements:

- The joining process needs to be precise, without generating significant distortion. This is primarily because of the fine details that need to be joined with todays de facto standard joining method; laser welding. A misalignment will cause a hole, not a joint so shape stability is crucial. Secondly, shape stability is needed because the stack of BPP will be mechanically compressed to ensure good contact between the MEA and the BPP. If distortions become too large a stack can become geometrically unstable, or stresses can be built-up in the stack that cause uneven pressure on the MEA, giving uneven conditions for the fuel cell operation inside the stack, leakage of H_2, or even stack collapse.
- The joining process needs to provide a leak-tight joint that hermetically seals the inside from the outside. Coolant leaks will quickly deteriorate the stack functionality, and potentially also make the operation unsafe.
- The formed joints need to be strong. This is because the stack is mechanically compressed to make good mechanical contact between the MEA and the BPP. The joints are thus supporting a significant static load. In mobile applications the stack can also be subjected to significant oscillating loads that can cause fatigue. Joints that are too small or have an uneven or undesired/imperfect shape are especially sensitive to fatigue.
- The joints need to effectively conduct the electricity generated in the stack. A stack is essentially pairs of anode/cathode plates joined together and connected in series. Since every plate pair contributes ~0.6-0.8V means that several hundred joined plate pairs are needed to make a sufficiently large voltage. The absolute current level and the current density also becomes very large. Areas that cannot be permanently metallurgically joined, and thus are in mechanical contact only, need to exhibit a low interfacial contact resistance to facilitate effective electrical conduction.
- Furthermore, the joints should be as inert as possible in relation to the environment in the FC, both on the coolant and MEA sides. This is to reduce or eliminate the propensity for galvanic corrosion. The coolant used to cool the stack needs to be a dielectric with as low conductivity as possible, to reduce the risk of current being conducted to other parts of e.g. a vehicle or other parts of the construction that the fuel cell is powering. Therefore, the liquids used in the coolant formulation needs to have as low ion activity as possible, the corrosion processes on the coolant side should progress slowly or not at all, and the corrosion inhibitors used need to be very effective and specially designed for the task. Even so, one may need to attach ion exchange filters in the coolant circuit to maintain a sufficiently low conductivity.

There are a number of joining methods available of which laser welding is today’s de facto standard method whereas EMPT, brazing, soldering, and adhesive bonding are a few candidate technologies. Industrial mass scale joining of intricately shaped aluminium plate components to a large degree takes place within the heat exchanger industry, where Gränges has its core material competence.

Today, metal BPP tends to be joined primarily at the outer extremities. The complex internal channel flow pattern is typically not joined other than on a few spots or lines of all the myriad possible joint sites. Hence, the internally applied coolant pressure will act to make the plate bulge outwards somewhat. To counteract this bulging and to ensure that the coolant follows the intended flow pattern an external mechanical pressure is applied by a strong and rigid fixture made of heavy gauge metal plates, called endplates, that are connected by bolts. The stack is placed in between the endplates and the target pressure is obtained by tightening the bolts. The MEA is placed between each joined bipolar plate pair in the stack. The sealing between MEA and plate is made by means of gaskets, commonly made of polymers, and the externally applied pressure also ensures sufficient sealing between gaskets and MEA.

4.2 Laser welding

Laser joining is the go-to method for joining bipolar plates. It is fast, accurate, low cost and it has a relatively small equipment footprint. It is a safe and quiet process that can be used for welding and cutting alike. The energy input from the laser to the workpiece can be carefully controlled. No strict demands on working atmosphere or temperature are required by this method, and no toxic emissions or other residue is generated. The process lends itself to automation. However, as with all melt welding methods there will always be a risk of change of residual stress pattern post-welding (causes warping), heat affected zone (HAZ) formation, localized sensitization for corrosion. These can be limited by careful process control. Also, a melt welding may affect a coated surface negatively.

The main limitation with laser welding is the need for an intimate contact between the upper and lower plates where the laser beam melts the upper plate and the joint with the lower plate is made. If there is a too large gap between the lower and upper plate when welding, then no joint will form. Instead, a hole is made, and the bipolar plate will leak. Hence, the plate needs to be securely fixtured when welded but even so it is only safe to weld areas that have been formed especially for welding, the rest of the flow channel pattern is unwelded and held together by the externally applied compression force.

Since only a fraction of the internal plate/plate contact sites will be metallurgically joined it is necessary that the remaining contact sites, that are mechanical by nature, exhibit as low an interfacial contact resistance as possible. To do this the inside surfaces of the plates are typically coated with a suitable coating.

4.2.1 Production – laser welding

Two types of lasers are commonly used; solid state lasers (Nd:YAG) and gas lasers (CO_2). Solid state lasers have a wavelength of about 1 µm, which is shorter than the gas lasers typically used for welding. Fiber optical cables can be used to transmit the laser energy to where it is needed. Gas lasers use high-voltage, low-current power source to supply the energy needed to excite the gas mixture is used as a lasing medium. These lasers can operate in both continuous and pulsed mode, and the wavelength of the CO_2 gas laser beam is 10.6 µm, i.e. deep infrared or 'heat'. Fiber optic cable absorbs these wavelengths and is destroyed, so a rigid lens and mirror delivery system is used. Power outputs for gas lasers can be much higher than solid-state lasers, reaching 25 kW. The cost for lasers has decreased over the past years, while output power has increased.

There are various laser welding methods. One method is where the laser beam output, usually on a robot, is moved to follow the seam. Scanner welding is a technique where the beam is guided by use of mobile mirrors. This enables fast movement, dynamic, flexible, and precise welding.

The main supplier of laser welding equipment worldwide is Trumpf, and bespoke BPP welding cells are offered. Andritz Soutec AG is a Swiss supplier of laser equipment for joining bipolar plates [31], offers a system that can produce up to 1 BPP/s based on a benchmark weld seam of 2.5m. Soutec systems are offered by Schuler for complete BPP production lines. The current market behemoth within the field of industrial laser applications, including laser welding systems for BPP, is the German company Trumpf [32].

4.2.2 Internal coating on aluminium BPP, compatibility with laser welding

When joining the BPP using laser the metal becomes fully or at least substantially molten at the joint sites. This will locally disrupt or destroy surface coatings that are on the joint site. The coating material will be disrupted, disintegrated, evaporated or become incorporated in the joint. Locally, the function of the coating on both external and internal surfaces will thus become compromised. This is much the same situation as with coated stainless steel BPP that are used today.

On the H_2 gas side of the BPP the MEA will be placed far away from the joint sites. Assuming that the surfaces will be substantially dry thus gives that the risk of galvanic coupling with the moist laden MEA is low. On the exhaust side the same situation rules, but the risk of condensation on the inside surfaces may increase the risk of localized corrosion on areas where the coating is disrupted. On the coolant side there will be contact between coated and uncoated areas with a galvanic coupling between them supplied by the coolant. Therefore, efficient corrosion inhibition of the coolant is necessary. Such corrosion inhibitor formulations have been developed for brazed aluminium radiators in PEM FC applications, when working with stainless steel, graphite or other BPP materials. It is likely that the inhibitor formulations work similarly when also the BPP is made out of aluminium, but rigorous testing is nevertheless needed.

4.2.3 Laser welding of aluminium vs stainless steel BPP

The welding parameters for the two material groups are not identical since they are widely different. It is also altogether likely that a BPP of aluminium has a different thickness than that of stainless steel. A direct comparison is thus quite difficult, and the best outcome comes from optimization procedures for each material. That is, however, out of scope for this work, but general trends could be outlined to assess the impact on productivity.

The actual laser time in welding should be similar for similar thicknesses. A thicker material means a larger amount of energy is needed to melt the larger volume of material to form the joints. Several other material parameters like the reflectance, heat conductivity and heat capacity will also affect the amount of energy needed to form a joint. However, from a productivity perspective the time needed for handling the parts to be joined for fixturing and transport in the equipment is typically longer than that needed for the actual heat input in welding. One may also add several lasers that work in unison to execute the joining. From the perspective of formed plate geometry, it should not be any large difference between aluminium and stainless steel BPP relevant to production in laser welding.

4.2.4 Advantages and limitations – laser welding

Pros

- Established technology for BPP joining.
- Predictable and repeatable outcome when process is established.
- Predictable and low variable cost.
- Can be used for cutting as well as welding.
- No demands on working atmosphere.
- No emissions are generated in the joining process.
- No filler is needed.
- Allows for the use of low to medium strength aluminium alloys.
- Fast capacity/capability development of equipment in the past, expected also in the future.
- Full automation of welding process is possible.
- The welding process can tolerate a limited surface contamination.

Cons

- Aluminium welding parameters more challenging than stainless steel.
- At the weld site, a coating may become ruptured, cracked or otherwise negatively affected.
- Formation of HAZ during welding (fatigue, corrosion sensitization).
- Large initial investment.
- Joining time is proportional to weld length, making full internal flow path joining impractical.
- Plate fit-up extremely crucial, small misalignments may cause perforation and leakage.

4.3 Brazing/soldering

Brazing and soldering are both processes to join components that are separated by a gap heating to joining temperature, applying a metallic filler material that melts and is sucked into the gap by means of capillary pressure. The processes are well described in [33-36] and a short description is compiled here. The melt is distributed homogeneously into the gap and the capillary pressure forms the liquid into a meniscus inside the gap. Upon cooling the liquid solidifies and provides a leak free, permanent metallic bond. Brazing takes place at >450°C, and soldering is <450°C. Naturally, this difference in turn dictates a difference in the types of filler metals and fluxes that are used in the process. Additionally, it also dictates what type of application method can be used for the process to work.

Aluminium is the most commonly brazed material worldwide, with the overwhelming majority of all vehicle heat exchangers being joined in this way. This includes road transport (cars, trucks, heavy duty etc), aerospace, and marine applications. This includes heat exchangers used to cool fuel cell circuits. To an increased extent, brazing is used for stationary HVAC-R (heating, ventilation, air conditioning and refrigeration) that is used in e.g. buildings, industrial heat exchange and supermarket freezers/coolers.

Soldering of aluminium and its alloys is not as common as brazing, and is typically employed where strength and corrosion are of lesser importance than e.g. electrical/thermal conduction and leak tightness. It is currently mostly used in the electrical and electronics industry.

In both brazing and soldering of aluminium the surface oxide native to aluminium prevents successful wetting of the surface by the molten filler, and thus also inhibits joining. To reduce or eliminate the influence of the surface oxide on joining one need to add a substance called a flux to the filler composite. The function of the flux is to melt, wet the native oxide of the aluminium surface and flow over it, and then to react with the oxide. The result is that the oxide is dissolved, disrupted, broken up or otherwise moved to expose the pure metal surface underneath. Then, the filler metal needs to melt, wet both surfaces to be joined and then flow into the joint site to form a liquid meniscus between the still- solid component surfaces. After this the cooling should set in, during which the meniscus should solidify without liquation, dewetting or similar to provide a permanent metallic bond between the components. The above represent a chain of events that, if broken, results in no or dissatisfying joining.

4.4 Controlled atmosphere brazing (CAB)

Aluminium is the most commonly brazed metal globally, and CAB is by far the most common brazing technology today. Filler metals are typically composed of Al with 5-13% Si [37]. Additions of small amounts of Zn and/or Cu can be used to impose small alterations of corrosion potential relative to the non-melting parts. Heating to brazing temperature is normally made using furnace heating, see Figures 24 and 25. Gas burning torches, induction, or heat conduction from hot contact elements can also be used. The filler starts melting at ~577°C, and the upper part of the melting interval depends on how much Si is added. The brazing temperature is typically in the interval 595-605°C. The filler is typically applied to the non-melting parts as a cladding, forming a so-called brazing sheet. When the filler is added as a cladding one must avoid a gap between components. Filler can be applied as a preform (shim from sheet, or wire based forms – both common), as powder (rare) or as a paste (common) to facilitate localized joining.

The flux type normally used in brazing is of the Al-K-F chemistry. The flux composition at brazing temperature is normally chosen as $KAlF_4$, having a melting temperature of 552-562°C depending on the detailed chemistry and phase composition.

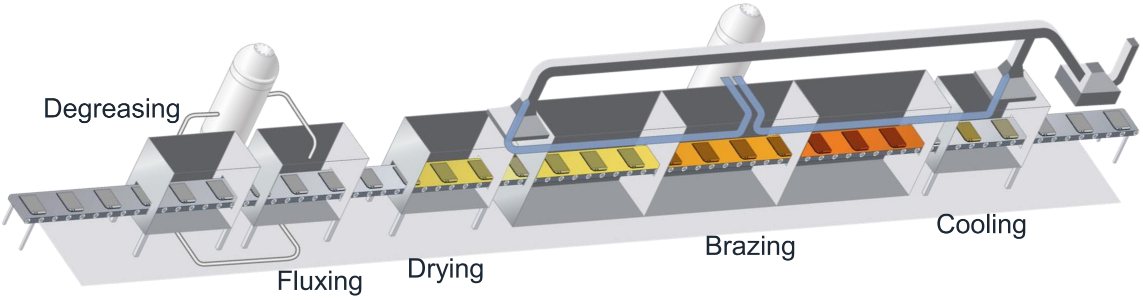


Figure 24 The principle build-up of a CAB line.

Figure 25 Examples of real CAB lines [38].

4.4.1 Production - CAB

There are many manufacturers of CAB production lines that can be found in certain niches and geographic locations, but the omnipresent and global leader of CAB line manufacturing is the Polish company Seco/Warwick. They currently have the broadest technology offering, a very good quality reputation, a global presence and are considered to give good value for money. They are present in all types of aluminium CAB brazing and are by a wide margin the biggest supplier of key-ready production lines.

Users of CAB almost exclusively produce components for heat exchange applications. The application segments are automotive heat exchange and stationary HVAC-R (heating/ventilation/air conditioning/refrigeration). The current main big producers of brazed aluminium within automotive are Denso, Hanon, Valeo and Mahle. However, there is a multitude of smaller brazing manufacturers. Additionally, there are many producers that are capable of brazing using different CAB techniques that use only small amounts of flux.

Traditionally, CAB is seen as the least costly joining method for aluminium heat exchangers. This is perhaps a bit unjust, as cost depends on a multitude of factors. Batch furnaces for CAB exist and are used in niche and small volume production. However, in mass scale serial production the use of continuous tunnel furnaces facilitates very high productivity, and productivity levels can be increased by suitable add-on equipment on an already existing line. This gives significant economic scale effects. For heat exchangers of the fin/tube and plate/bar types the CAB wins out, excepting the large air separator heat exchangers for cryogenic applications where VB is a preferred choice.

The production rate in the brazing of heat exchangers depends on the equipment set-up and the size and shape of the unit. The more complex the heat exchanger and the longer the heat has to be conducted into the unit the longer the time is needed. However, “simple” units like a condenser or a radiator weighing 1.5-3.5kg can be brazed at a rate of ~2/min in a 24/7 conventional set-up. A BPP pair can be brazed at a considerably higher rate, but the actual magnitude would depend on the size, shape and weight of the plates as well as the fixtures needed to keep the plates locked in place during the brazing procedure.

The cryolitic brazing flux needed to facilitate joining will cause the coolant to contain ions of F and K post brazing unless thoroughly cleaned. Indeed, the coolant used for fuel cells need to be as non-conductive as possible and special additive packages have been developed for the use in fuel cell applications.

4.4.2 Internal coating on aluminium BPP, compatibility with CAB

If a metallurgical joining can take place on all points/surfaces in contact, then a coating to make electrical conduction easier on such areas is no longer needed. Actually, a coating applied to the internal surfaces of the plate would not be a viable prospect for clad aluminium brazing sheet. A coating would prohibit effective flux action, prevent disruption of the native oxide layer present on all aluminium surfaces and make wetting of the surfaces to be joined difficult or impossible and no joining would occur. Thus, for clad aluminium brazing sheet internal coating is not a viable prospect.

If a coating is still considered necessary for some other reason, then the coating itself needs to withstand high temperatures and the filler has to be applied as a preform or paste. Then, however, the filler does not join with aluminium but with the coating material. The filler must thus be adapted for whatever material system the coating consists of. If adaptation is not made, then it might result in poor joining or a disrupted or destroyed coating – locally or more extensively.

4.4.3 Braze joining of aluminium vs stainless steel at normal pressure

Stainless steel can be joined in brazing, but the processes differ markedly from those used for aluminium. There are several processes that can be used to braze stainless steels-furnace, induction, resistance, or torch. Most stainless steels can be brazed with several different filler metal families, including silver, nickel, copper, and gold. In most applications, filler metals are selected based on their mechanical properties, corrosion resistance, service temperature, and compatibility with the base metal. Brazing of formed plates is typically made in furnaces, using a thin Cu foil interleaved between the plates to be joined. It can be a simple rectangular shape or a punched preform with the Cu located at the prospective joint sites. One or the other is chosen for practical and cost reasons. The plate/preform assembly is then heated in inert gas furnace with a H_2 addition (forming gas) up until the Cu melts, wets the countersurfaces and flow to form a metallic joint. This basic procedure is the most commonly employed in the brazing of stainless steel plate heat exchangers, see Figure 26.

Compared to aluminium, stainless steel brazing furnaces utilize a more costly batch set-up to accommodate the use hydrogen gas in the furnace atmosphere, and a considerably higher temperature. The H_2 has a fluxing function and no additional flux is typically needed. Wet hydrogen atmospheres can be used to braze parts that are slightly contaminated with hydrocarbon substances. The use of Cu as a preformed filler is often but not always a considerable cost. Moreover, the Cu filler typically makes recycling of the metal back to other steel grades challenging. All in all, the cost of brazing a BPP using atmospheric pressure furnaces should be lower for aluminium than for stainless steel.

Figure 26 A copper brazed stainless steel plate heat exchanger for liquid-liquid heat exchange.

4.4.4 Advantages and limitations – CAB

Pros

- Permanent metallurgical, leak free and gas tight joints result in CAB.
- Low, predictable variable cost and repeatable easy-to-monitor-and-control process.
- Few emissions made in the CAB process.
- Process lends itself to joining in the volume interval of ~10^3 and upwards.
- Very small areas, narrow lines and thin sheet "easily" joined.
- Process lends itself to mass scale automation.
- Braze clad plates are possible to make using established plate cladding methods.
- Very good electrical conduction through joint.
- Small risk of galvanic corrosion between base plates and filler.
- CAB gives joints with high static and fatigue strength.
- Material+process combination is comparable/compatible with today's heat exchangers for PEM FC.
- Internal overlap joining possible also for very complex geometry.

Cons

- AlKF flux residue post joining. Cleaning is most likely required.
- If cladding all over surface is not allowed or impractical, then filler needed for joining must be added as a preform (shim, wire, paste or powder).
- Special constraints on atmospheric working conditions in CAB applies.
- Heating of whole plate pair for joining, localized heating difficult (but possible).
- Process may affect geometry by warping during cooling.
- If the coated BPP surface is to be part of the joint, then the surface coating is likely ruptured, cracked or otherwise mechanically or locally chemically affected.
- Filler alloy elements reduce aluminium recyclability, similar to that of heat exchangers.
- Utilises low to medium strength aluminium alloys.

4.5 Vacuum brazing (VB)

The VB technique, while used to join more than 100 Ktons of aluminium products per year, is much less used than CAB. Filler metals are typically composed of Al with 8-13% Si and 0.7-3% Mg [37]. Additions of small amounts Cu can be used to impose small adaptations of corrosion potential relative to the non-melting parts, either to match or to make a dedicated difference. The filler starts melting at ~555°C, and the upper part of the melting interval depends on how much Si and Mg is added. The brazing temperature is typically in the interval 595-605°C. The filler is typically applied to the non-melting parts as a cladding, forming a so-called brazing sheet. When the filler is added as a cladding one must avoid a gap between components. In this technique, it is also common to add the filler as a shim or powder to the joint site. Brazing is typically made in batch furnaces like that shown in Figure 27.

In vacuum brazing the furnace atmosphere quality is decisive for joining and no external flux is added. Instead, the fluxing action is executed by Mg that breaks up the oxide, sublimes and scrubs the furnace atmosphere from remnants of oxygen and water vapour.

Figure 27 The appearance of a batch VB furnace for aluminium [39].

4.5.1 Production - VB

The use of vacuum furnaces for heat treatment and brazing applies to many more materials than aluminium, and the market for VB is thus much more fragmented than that for CAB. The use of VB is typically considered to be more difficult and slightly costlier than CAB. Typically, the investment cost is slightly higher for VB but the equipment footprint is much smaller and the variable costs are also much more limited. However, requirements on part fit-up and surface cleanliness are higher. Users that operate both CAB and VB tend to stress that their respective total upsides vary depending on a multitude of parameters, one technique is not exclusively outperforming the other. However, VB seems to be the method of choice for applications that require i) very large components, ii) very intricate demands on joint geometry iii) many internal joints that are inaccessible for externally applied flux, iv) high post-brazed internal cleanliness demands and v) good aesthetic appearance. Although the use of continuous furnace production set-ups are available the go-to set-up is batch processing. A batch process is flexible with respect to many parameters such as part size, part geometry and production volume to a certain point but has unyielding upper limits on productivity.

Users of aluminium VB are almost exclusively producing components for the use within heat exchange. The application segments are automotive heat exchange and stationary HVAC-R (heating/ventilation/air conditioning/refrigeration). The main producers of brazed aluminium within automotive are Denso, Hanon, Valeo and Mahle. However, there is a multitude of brazing manufacturers ranging in size from small to large that are capable of brazing using different CAB and related brazing techniques. Within the joining of plate/plate heat exchangers the VB is a strong and competitive technology that is on par with and in many cases outcompete CAB.

4.5.2 Internal coating on aluminium BPP, compatibility with VB

The reasoning for VB is to a very large the same as for CAB. If a metallurgical joining can take place on all points/surfaces in contact, then a coating to make electrical conduction easier on such areas is not needed. The multitude of metallic joints that are formed should be sufficient to conduct the electricity, and with lower losses than a mechanical contact can supply.

A coating applied to the internal surfaces of the plate would not be a viable prospect for clad aluminium brazing sheet. Since VB is a flux-free exudation brazing process that relies on Mg evaporation and disruption of the surface oxide any coating would prohibit effective wetting, prevent disruption of the native oxide layer present on all aluminium surfaces and make joint formation difficult or impossible and no joining would occur. Thus, for clad aluminium VB sheet internal coating is not a viable prospect, and even more strongly than for CAB where a liquid flux can assist in wetting the surfaces and chemically disrupt the hindrances on the surfaces.

If a coating is still considered necessary for some other reason then the coating itself needs to withstand high temperatures and the filler has to be applied as a preform. Paste is not a viable option for VB. Then, however, the filler does not join with aluminium but with the coating material. The filler must thus be adapted for whatever material system the coating consist of. If adaptation is not made, then it might result in poor joining or a disrupted or destroyed coating either locally or more extensively. All in all, surface coating should be avoided if VB is used for joining.

4.5.3 Vacuum brazing of aluminium vs stainless steel BPP

Stainless steel can be brazed in vacuum, with much the same basic type of equipment as that used for vacuum brazing of aluminium, with similar vacuum levels but with much higher target temperatures. Also, the steel grades typically have a nickel addition and the filler for these stainless steel grades appear to be based on nickel alloyed with boron and silicon. The braze filler is typically applied as a foil or a preform. The higher temperatures used in the vacuum brazing of steel compared to aluminium requires more choice of more durable materials from which to build the furnace. As for normal pressure brazing using copper, the typical product with stainless steel appears to be heat exchangers, see Figure 28 for an example.

All in all, the cost of brazing a BPP using vacuum furnaces should be lower for aluminium than for stainless steel. The reason for this should be sought in the higher working temperature specifications for vacuum brazing of steel. The higher temperatures give higher heating and cooling times, and might require bespoke stress relieve procedures of the steel plates after brazing to offset any dimensional change that occurs during the brazing.

Figure 28 An example of a nickel vacuum brazed stainless steel plate heat exchanger for liquid-liquid applications.

4.5.4 Advantages and limitations – VB

Pros

- Permanent metallurgical, leak free and gas tight joints result in vacuum brazing.
- Medium predictable variable cost and repeatable easy-to-monitor-and-control process.
- No emissions made in the process.
- Very small areas, narrow lines and thin sheet “easily” joined.
- Process lends itself to mass scale automation.
- Braze clad plates are possible to make using established plate cladding methods.
- Very good electrical conduction through joint.
- Small risk of galvanic corrosion between base plates and filler.
- VB gives joints with high static and fatigue strength.
- An internal coating can be dispensed with.
- No flux residue post joining.
- Material+process combination is comparable/compatible with today’s heat exchangers for PEM FC.
- Allows for the use of medium to high strength aluminium alloys.
- Internal overlap joining possible also for very complex geometry.

Cons

- If cladding the plates before forming is impossible or impractical, then filler for joining must be added as a preform (shim, wire, or powder).
- Very strict constraints on atmospheric conditions applies during vacuum brazing.
- Heating of the whole plate pair needed for joining, localized heating impossible.
- Process may affect geometry by warping during cooling.
- If the coated BPP surface is to be part of the joint, then the surface coating is likely ruptured, cracked or otherwise mechanically or locally chemically affected.
- Filler alloy elements reduce aluminium recyclability, similar to that of heat exchangers.
- Mg and MgO condenses on all surfaces inside the furnace, special and costly annual maintenance needed.
- Brazing temperature is high, and the material becomes fully soft during the process.
- Might be a slow technique unless bespoke continuous furnaces are made.

4.6 Soldering

The process of soldering is much like brazing with a few notable differences. The low melting temperature (<450°C) makes cladding onto an aluminium core metal alloy practically impossible, as the roll cladding process is a hot rolling technology that typically takes place at a temperature of 450-500°C. Also, the low temperature used in soldering makes filler metals similar to the base metals practically impossible and thus galvanic corrosion is unavoidable without bespoke efforts to deal with it.

Most solder alloys developed over the course of history have been based on Pb and Sn, with minor additions of other elements depending on the intended joint properties and the type of base metals used. However, the presence of Pb in solders has historically caused a lot of grief and is today either frowned upon, avoided, outright banned by law and treaty or on the way to be outlawed. For a comprehensive list of the historically important and presently commonly used solder alloys look in [40]. Lead-free solders in commercial use may contain Sn, Cu, Ag, Bi, In, Zn, Sb, and traces of other metals. They tend to contain significant amounts of many elements and it is highly likely that the corrosion potential of said solders will be very different from that of the coated base plate.

4.6.1 Production - soldering

Soldering has been one of the go-to methods of joining in the electrical and electronics industry. It is used for joining electronic components onto circuit boards, connecting them to data/address bus components and electrical power supply. The soldering also provides a mechanically durable connection to the circuit board. The electrical and electronics industry is extremely diverse and versatile, having very broad spectra of requirements for soldering attachments. Many different metals, alloys and non-metallic components can be joined. This has led to a plethora of filler alloys, filler dispensation techniques and heating arrangements to provide a reliable filler flow and joint formation. Reputedly the success rate in joining in this industry is very high. Additionally, the joining technologies have been developed for decades to provide high flexibility, a high degree of automation, a low operating cost, and a wide/diverse flora of technology and equipment suppliers. An example of an automatic wave dip soldering machine is seen in Figure 29, aimed for lead-free soldering of printed circuit boards.

The hardware and technology solutions are considered among the least costly. The operating cost of the equipment can be made very low, depending on technology choice and set-up. However, the variable cost of the filler is significant. The content of noble, semi-noble and rare metals provides for costly input material in this respect.

Figure 29 An automatic wave soldering machine for lead-free soldering of printed circuit boards with 300mm size from Shenzhen Jaguar Automation Equipment Co. Ltd

4.6.2 Internal coating on aluminium BPP, compatibility with soldering

As with brazing using the CAB and VB technologies soldering can be used to make permanent metallurgical joints between plates that conduct electricity very well. A coating to make electrical conduction easier on such areas is thus not needed. The metallic joints that are made should be sufficient to conduct the electricity, and with lower losses than a mechanical contact can supply.

If a coating is still considered necessary for some other reason, then the coating itself needs to withstand temperatures up to about 450°C and the filler has to be applied as a preform. Paste is not a viable option for VB. Then, however, the filler does not join with aluminium but with the coating material. The filler must thus be adapted for whatever material system the coating consists of. If adaptation is not made, then it might result in poor joining or a disrupted or destroyed coating – locally or more extensively. All in all, surface coating should be avoided if VB is chosen as a joining method.

4.6.3 Soldering of aluminium vs stainless steel BPP

As indicated above, there are many different solder alloys available for aluminium, and most of them can also be used for the soldering of steel. The key to successful soldering of aluminium, and of stainless steel, lies in three key areas: the flux, the solder, and the heat source. A correct choice can result in sound and reasonably strong joints. Factors that affect the set-up are the shape of the material to be soldered, the size and shape of the joints and the scale and form in which the soldering is to be supplied. Steel can be soldered using furnace-, torch-, flame-, or induction heat sources, very similar to those of aluminium.

For stainless steel grades silver-based solder can be used. It works well for most common metals, including mild steel, copper, brass, cast iron and can be used in dissimilar metal joining. For aluminium the intermetallic bond can be achieved with several filler alloy combinations, such as tin-zinc, tin-silver, SN100C ™ and ALUSAC-35™ are all good at creating this special bond. There appear to be few, if any, industrial mass scale applications involving soldering of steel grades, the reason is unclear. Aluminium, on the other hand, seems to be more prolific soldering use cases, primarily within the field of electronics. All in all, considering the higher exclusivity of the fillers for steel it is likely that the cost of soldering in stainless steel is higher than that of aluminium.

4.6.4 Advantages and limitations – soldering

Pros

- Permanent metallurgical, leak free and gas tight joints result in brazing/soldering
- Medium variable cost and repeatable easy-to-monitor-and-control production process
- Few emissions made in the process
- Very small areas or extremely narrow lines easily joined
- Process lends itself to mass scale automation
- Soldering is made at relatively low temperature, and warping during cooling can be limited or eliminated.
- Very good electrical conduction through joint.
- Localised and furnace heating equally possible and established/industrialised.
- Allows for the use of high strength aluminium alloys.
- Internal overlap joining possible also for very complex geometry.

Cons

- Clad base metals are not possible to make using established cladding methods. Filler needed for joining *must* be added as a preform (shim, wire, paste or powder).
- Variable cost of filler is high.
- Special constraints on atmospheric working conditions in soldering might apply.
- Soldering may give corrosion sensitive joints with comparatively low (but still acceptable?) strength.
- If the coated BPP surface is to be part of the joint, then the surface coating is likely ruptured, cracked or otherwise mechanically or locally chemically affected.
- Commonly used inorganic fluxes (e.g. ZnCl) are corrosive to aluminium, and resinous fluxes tend to be hazardous to health. Cleaning and EHS restrictions apply.
- Alloying elements in the filler will significantly interfere with aluminium recycling.
- Significant risk of galvanic corrosion between base plates and filler.
- Soldering temperature may be high enough to cause at least limited softening of the plate.
- Joint material strength likely lower than the aluminium base metal.

4.7 EMPT

4.7.1 Basic observations and background

This is probably the most esoteric joining method of the ones mentioned in this report. It is a technology with several difficult-to-clear hurdles but also a promising method if or when said hurdles are either removed or adapted to. A clear advantage of the technology is that one and the same EMPT-pulse generating equipment, Figure 30, can be used both for forming, punching, and welding. The main differences are found in how these operations are set up.

Electromagnetic pulse technology is a forming and joining method where the welding occurs at room temperature, i.e. in the solid state [41]. The welding action is actuated by rapid acceleration of one workpiece into another. The acceleration is generated by an electromagnetic pulse generated by discharging an electric condenser array into a suitably shaped tool. The pulse induces Lorentz forces in the surface of the sheet and accelerates it towards a countersurface where it impacts at supersonic speeds, creating a metallic, permanent and metallurgical gas tight joint. This technology is most efficient in metals that are good electrical conductors, such as aluminium or copper though various steel grades are also joined in this way. Welding-wise, it is most similar to explosion welding and the actual metal-metal joint is made in the same way. A limitation is thus the risk for geometry changes of the plate during the welding process. Rigid support is thus needed to counteract undesired geometry changes during manufacture.

Figure 30 Appearance of the pulse generator equipment in EMPT and a welding box/booth [42].

4.7.2 Production - EMPT

The primary suppliers of this type of technology, at least in Europe, are the German based company PST Products Gmbh [43] and the France based company BMAX [44]. The heart of the equipment is the supercapacitor storage banks and the adhering charging/discharging electronics. Since the stored electromagnetic energy needs to be expended rapidly, but not too rapidly, particularly the discharge electronics needs to be carefully controlled. The flyer plate needs to contact the mating plate at the correct rate to facilitate a good, welded joint.

As the electromagnetic pulse needs to be localized to the areas of welding it is necessary that the field is concentrated to said areas to avoid affecting other parts of the plate. This is done by a dedicated field focusing tooling piece. The geometry of the field focus device is adapted to and unique to the shape of the plate and pattern to be welded. A change of design thus requires a new field focus tool. Also, since the field is not as sharply defined as e.g. a metal tool there are limitations to how small areas and narrow lines can be produced. However, EMPT has proven to reliably and repeatably join even very thin (~20µm) thick formed foils in practice. Nevertheless, it is likely that EMPT welding would be constrained to areas where local contact between plates can be guaranteed. This is because small misalignments may tear the plate and cause a hole, much the same as for laser welding.

In practice EMPT welding (and cutting, forming, crimping) can be made in automated and robotized environments dedicated to mass production. Process quality in any type of EMPT operation is made through discharge time and intensity measurement for every pulse and is thus easily and reliably made. There are very few things that can induce variations in the process once it is set up. For example, there are no moving parts in the welding machinery, and the supercapacitor banks deliver the same performance from discharge to discharge with little or no deterioration. The energy and intensity is measured every time a discharge is made. Once a capacitor or the charge/discharge electronics fails it can be spotted in the very first occasion of failure by the discharge time/intensity measurement, and thus large numbers of components that fail in joining can be avoided.

4.7.3 Internal coating on aluminium BPP, compatibility with EMPT

Because of the physics and nature of the joint formation in EMPT, a coating would be expected to be jetted out form the joint as it forms. Alternatively, it could become a part of the joint itself as the flyer impacts onto the plate beneath it. However, the presence of a coating is not automatically a positive or neutral feature as it can very well interfere with joint formation. Therefore, if a coating is necessary, it is most likely a positive feature if the coating could be localized to areas that are not intended to be joined, with the areas to be welded left bare.

4.7.4 EMPT joining of aluminium vs stainless steel BPP

To weld successfully using EMPT the induction of Lorentz forces into the surface of the flyer is necessary to accelerate it onto the plate beneath. This force generation becomes more efficient the better the conductor the flyer is. Since aluminium is at least 3-5 times better conductor than stainless steel it is likely that a smaller discharge is needed to generate a sufficient welding impact for aluminium. However, stainless steel is, despite the conductivity difference still an excellent conductor. Therefore, one should expect the differences in requirements for the welding set-up to be small. The handling and fixturing of an aluminium BPP during the welding procedure should also be similar to that of a stainless steel. All in all, the cost of joining stainless steel should be similar in EMPT, or only slightly higher, compared to that of aluminium.

4.7.5 Advantages and limitations – EMPT

Pros

- Permanent metallurgical, leak free and gas tight joints result from EMPT welding.
- No filler needed for joining, whether metallic or otherwise.
- No heating is needed for joining, no HAZ is made.
- Very low variable cost and repeatable easy-to-monitor-and-control production process.
- No emissions are made in the process.
- No constraints on atmospheric working conditions.
- Process lends itself to mass scale automation.
- Allows for the use of low, medium, and high strength aluminium alloys.
- Internal overlap joining possible.
- Can tolerate some surface contamination without adverse effects.
- Forming, punching and joining might be combined in one equipment.

Cons

- Joining process can affect plate geometry.
- Joining small areas or narrow lines is challenging.
- Complex joint patterns are challenging.
- At the joint site a coating is likely ruptured, cracked or otherwise mechanically affected.
- Large initial investment.
- Long joint lengths can require multiple joining pulses, affecting productivity.
- Emerging technology, unfamiliar to the mainstream joining industry and engineers.

4.8 Adhesive bonding

4.8.1 Adhesives - a speculative approach

This section is speculative, compared to the other joining methods mentioned in this report. It is included since adhesive joining, when introduced with an affordable and suitable adhesive using a well-adapted application method, it seems to outcompete other joining methods quickly and permanently. Adhesives can be made to work well in the temperature range normal for PEMFC and can also be made to withstand the presence of dilute acids. Also, much work is being done in academia and industry to make adhesives conduct electricity in a good way.

There are several approaches towards electrically conductive adhesives, the simplest being an addition of conductive fillers (graphite, graphene, carbon nanotubes, metal powders, …) into a non-conductive resin. This is often combined with other material requirements, like environmental friendliness, low CO_2 footprint and bio-based sourcing. Looking at a selection epoxy-based adhesive solutions already on the market with reported resistivities $<0.005\Omega$cm we find e.g. EP79FL, EP21TDCS-LO, FL901S and EP3HTSDA-2 [45]. These have fillers made from silver or silver coated nickel powders, and likely command a high price. Whether these and other existing adhesive solutions have a good enough electrical performance to suit metal BPP applications, and tolerate the chemical environment in the PEM FC, are open questions. In summary, adhesives for the joining of metal BPP are either not in existence or have at least not been validated for this application yet.

4.8.2 Basic observations and background

Adhesive joining, gluing components to each other, has been established in the automotive industry for many decades. The joining of metal components is somewhat more recent but still has about a half century of application. Development of adhesive joining of aluminium components was spearheaded by NASA and Boeing in the 1970'ies for the space shuttle, and it has been a staple of component joining for military aircraft since the 1980'ies, replacing riveting and melt welding. In automotive structural applications adhesive joining of aluminium was first introduced on a big scale to produce the Lotus Elise in the 1990'ies.

However, the need for electrical grounding of exposed components sometimes limits the application of adhesives in critical automotive applications, especially load carrying or safety components. This can be remedied in some cases by connecting components using cables attached using rivets or melt welds. It is also increasingly remedied as electrically conductive adhesives are developed, also for aluminium and dissimilar material joining, and can be obtained off the shelf. For example, PTC heaters are glued since decades, with the glue joining the aluminium fins/plates and the PTC-active aluminium titanate ceramics.

As of the writing of this report, there are many scientific publications on the subject of joining BPP using adhesives, and many patents as well. There are, however, no commercial examples of adhesives to join BPP for the purpose of conducting the large electrical currents that are generated in the fuel cell. The adhesive applications are all targeted towards the attachment of gas sealant and gasket materials [46]. However, said adhesives are tried and tested for other metals than aluminium and coating materials than the ones used in the BALBAS project, and must at this stage hence be considered hypothetical, or at least unproven, for joining these particular materials with aluminium.

4.8.3 Production – adhesive joining

Industrial scale adhesive joining can be made as a manual operation but is typically made in fully automated robotic machines or cells. There, components are placed, and adhesive is automatically portioned out either as liquid/paste or as a solid film or film preform. The various methods are e.g. application using pneumatic guns, electrically actuated guns or jetting guns/nozzles. Further, adhesive application can be made using wheel/roll, spraying or even brush/trowel systems. Also screen-printing deposition of adhesives is possible in production. The curing method depends on the material types to be joined and the adhesive type. Curing is made either using time in normal atmosphere, exposure to UV radiation, exposure to mechanical pressure, or moderately elevated temperature (100-200°C). Localized adhesive application makes internal joining between plates possible along all the contact points and lines. A fully joined internal network to define the flow path provides a very strong and stiff plate. Depending on the detailed set-up, productivity in adhesive bonding can become *very* high and full contact length joining does not necessarily affect productivity perceptibly.

There are a multitude of hardware suppliers for adhesive application. The best supplier choice will vary depending on adhesive type, application method and the production rate required. However, for the use in PEMFC, the adhesive is required to conduct electricity very well and the variety of such adhesives is limited. Therefore, the variable cost of the adhesive as such should be expected to be high.

4.8.4 Internal coating on aluminium BPP, compatibility with adhesive joining

When joining the BPP using adhesives using normal room temperature or low temperature curing the metal does not become affected to any appreciable degree. This will not disrupt or destroy surface coatings that are on the joint site and the function of the coating will not be affected either on the H_2 gas-, exhaust- or the coolant-sides.

Supposing that a sufficiently electrically conductive adhesive was developed, there would not be a need for a coating on the coolant side since the adhesive could be applied to all joint sites, given that a suitable application method is chosen. One could thus potentially dispense with a coating on the inside for the purpose of transporting the current from one plate to the next. Should a coating still be needed for some other reason it is important to realise that the adhesive should be made to join the coating materials with each other, not with aluminium.

4.8.5 Adhesive bonding of aluminium vs stainless steel BPP

The adhesive application process does not differ in any way depending on the plate material. What may differ between them are the pretreatments needed to make the adhesive work as intended. Also, the detailed adhesive composition may vary between them which in turn may affect the choice of curing method and the curing duration. Since aluminium provides a higher thermal and electrical conductivity than SS, it might be more suited to adhesive since the conductivity of the adhesives are worse than that of the metals. At this stage there is no definite indication to show that either SS or aluminium works better than the other using adhesive joining of BPP.

4.8.6 Advantages and limitations – adhesive bonding

Pros

- Superficially, adhesives provide a simple and intuitive joining process.
- Electrically conductive adhesives can be found on the market.
- Joining is made at low temperature (curing at <200°C).
- Adhesive joining is insensitive to plate material thickness.
- Adhesive joining lends itself to the whole volume spectrum; from few to millions.
- Leak free and gas tight joints can be made.
- Adhesive filler material can be burnt off in metal recycling processes.
- Joining is made without affecting a pre-existing coating.
- Low to high initial investment depending on application method.
- Adhesives will most likely not affect the properties of a superficial coating material.
- Allows for the use of low, medium, and high strength aluminium alloys.
- Full and partial internal overlap joining have similar productivity.
- Extremely high application rates are possible, with some application methods suitable for 4000-5000 cycles per minute.

Cons

- Electrically conductive adhesives for BPP not validated in any way.
- Extremely clean sheet surfaces are typically needed to make a strong joint.
- Temperature and chemical long-term durability uncertain/unvalidated.
- High current density stability uncertain in use.
- Uncertainty on electrical conductivity through joint.
- Depending on set-up, curing of the adhesive might be time consuming and require heat treatments.
- May cause emissions in the recycling chain.
- Filiform corrosion is a risk when polymers are clad onto aluminium.
- Probable high variable cost of adhesive and curing related processing.

4.9 Summary and discussion on joining technologies

There are, obviously, several technologies for joining BPP that are possible and one that is established and at least one that has potential after longer development. It is not useful to put dollar values, detailed productivity thresholds, detailed environmental sustainability opportunities or technical limitations in stone as it is design dependent and flows with market conditions. Also, development is continuous and today's hurdles, when overcome, may give other technologies an advantage of present state-of-the-art technology. At present, the laser welding is the method of choice and has reached that position because of a combination of good properties. These are e.g. the low variable cost production of even small volumes of plates, good repeatability and manageable investment costs.

In the short to medium term, it is likely difficult to outcompete laser welding. The technology is firmly entrenched in all metal BPP business. On the longer perspective, when very high production volumes can be expected, the situation might look different. However, once a technology has taken hold in an area it is often difficult to exchange it for other technology unless a very clear technical and cost advantage is to be had. Whether that is possible is at present very speculative.

4.10 Conclusions - joining

The established laser welding of BPP is difficult to displace.

Several alternatives to laser welding exist that could offer unique advantages, also in the medium to short term.

In the long term there are further alternative to laser welding that require significant development.

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