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Innovative welding conception for thin-walled sheet metal components

Axel Jahn*, Benjamin Kessler, Andrea Berger, Marko Seifert, Teja Roch

Fraunhofer-Institute for material and beam technology IWS, Winterbergstraße 28, 01277 Dresden, Germany

Abstract

Welding of thin-walled sheet metal structures is a challenging task in various applications. For bipolar plate manufacturing, complex requirements regarding effective welding speed, reliable welding process, high surface quality and minimal distortion have to be fulfilled.
A new welding conception for 100 µm stainless steel strip material was fundamentally developed, using a continuous processing in roll-to-roll principle with laser welding in the roll gap. Weld seams can be produced along and transverse to the strip running direction by using a fast scanner system, achieving very high welding speed of 30 m/min and more. High seam quality, virtually no damage of coated outer skin and minimal welding distortion demonstrate the technological potential.
The set-up including roller system, strip guiding and laser optics will be presented as well as results of process development. Potential application in fusion cell bipolar plate manufacturing will be shown referring complex process chain of strip coating, forming and welding.

Keywords: Laser welding; Hydrogen; Bipolar plate; Stainless steel;

1. Motivation

For the European energy transition, alternative drive solutions must be found, especially for the transport sector. Hydrogen-powered fuel cells (FC) are a promising approach to this. However, for successful widespread use of fuel cells, technological developments still need to be driven forward, particularly with regard to cost-efficient and high-rate production. In the production of the currently favored proton exchange membrane fuel cells (PEMFC), the manufacture of the metallic bipolar plates (BPP) currently represents a significant obstacle.

Specifically, the batch production currently used cannot be significantly expanded in terms of output. Main obstacles are the limited speed and quality (e.g. distortion) in the weld production. A new approach for the entire BPP production-chain based on roll-to-roll (R2R) concept is under development, which promises high output rates and high quality, especially in welding operation.

2. State of the art in the production of metallic bipolar plates

The electrochemical reaction of the gases hydrogen and oxygen with the release of electric charges takes place at the BPP. Metallic BPP (PEMFC) usually consist of two half-shells (cathode and anode) made of stainless steel sheets (e.g. 1.4404) of a thickness of 75 - 100 µm. For corrosion protection and excellent electrical properties, these strips are coated, usually with platinum or gold. In the BPP production, the half-shells are formed in individual steps and then welded, e.g. by laser welding in batch production. Joining of the two half-shells creating the BPP, have to meet two main targets (see Fig. 1):

- reliable contacting of cathode and anode shell inside the flow field and
- sealing welds in the edge area to close the flow field, the manifolds as well as the inlets and outlets.

Laser remote welding is used for welding the BPP in the state of the art. In this process, the plates are pressed together with a clamping device and welded in an overlap joint in full-penetration or even half-penetration of the lower sheet. The following limitations exist for the process execution:

- maximum welding speed at ca. 1 m/s due to humping effects, when using standard single-mode laser
- very sensitive regarding gap-bridging; max. 10 % of sheet thickness
- local destroying (weld seam) and negative affection (heat affected zone) of surface coating, at least at upper side
- unsymmetrical temperature field leads to complex weld distortion phenomena of single BPP, and subsequently leads to difficulties in packaging or even damage of the sensitive GDL membrane.

Development work is published for welding speed increasing by using specific beam modulation approaches, but physical limits due to humping effect are existing as well as limitations in transformation of the very high speed values to welding contours of real parts.

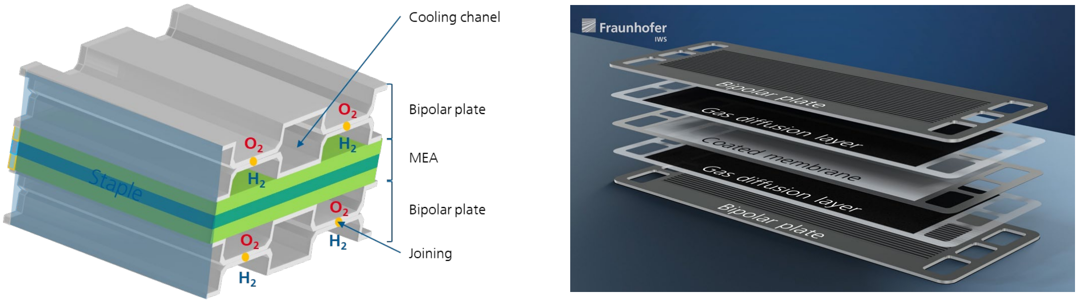

Fig. 1. Principle structure of a PEM fuel cell stack with metallic bipolar plates

3. Roll-to-roll production concept

A new holistic production conception is under development within research projects under participation of serveral Fraunhofer institutes, focusing on a continuous process flow with potential high output capacity. This concept is based on a continuous sequence of all production steps for manufacturing the BPP in a roll-to-roll (R2R) approach. Currently, the single production steps are under development with the intention of the final interconnection in a later development phase. The target of the strip moving speed was defined at the value of at least 30 m/min in order to achieve economically interesting output rates.

This roll-to-roll production concept for metallic BPP contains:

- application of a new carbon coating in R2R with competitive electrical and corrosion properties

- new forming process (hollow embossing rolling) of half-shells (Fraunhofer IWU, not topic of this paper)
- continuous joining of the half-shell strips to BPP using laser roll welding and bonding
- separation of single BPP out of the carrier strip by laser remote cutting

Separate steps of the production chain and their interconnection are patented by some of the authors. Fig. 2 shows the schematic overview of the R2R process flow.

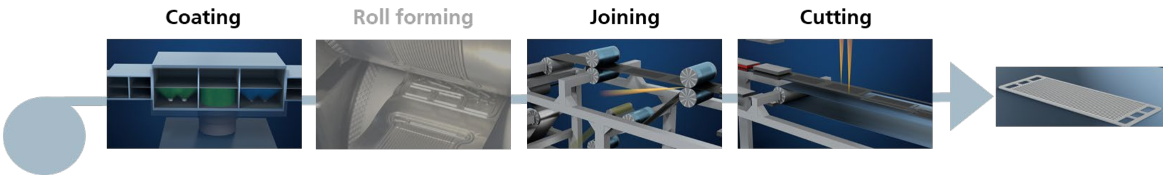

Fig. 2. Overview of process chain for roll-to-roll BPP production

4. Roll-to-roll joining process for BPP

4.1. Joining concept in roll-to-roll configuration

The joining process is under development according the requirements of the continuous R2R production. The two pre-manufactured (coated and formed) endless strips are inserted into the joining unit. The half-shells (anode and cathode side) are welded together by laser, focused into the gap formed in-between (see Fig. 3). The so-called laser roll welding will be potentially applied by cooperative fast scanner systems in a future development phase.

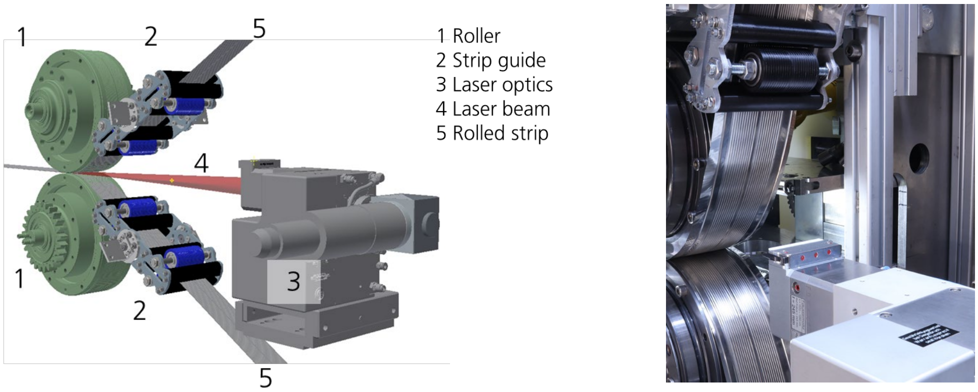

Fig. 3. Basic concept of the welding process in the roller gap; schematic view (left) and view into lab set-up (right)

The application of the two joining processes (welding and bonding) are defined according to their characteristics; while adhesive bonding taking over the sealing function in the edge areas, laser welding realizes the electrical contacting in the flow field, closes the BPP in longitudinal direction and keeps critical shear loads away from the bonded joints. The joining process and the geometry of the BPP have to be adapted and developed to meet the specific requirements. In this paper, only the laser welding process is described. Fig. 3 shows the detailed view into the joining unit.

The design of the BPP must be adapted in such a way that the joining operations can be carried out and high strip running speeds can be achieved. Welding of seams oriented along the strip moving direction can be realized preferably. Transversal seams have to be oriented under an angle down to ca. 10°, due to the superposition of the strip movement and the movement of the laser beam.

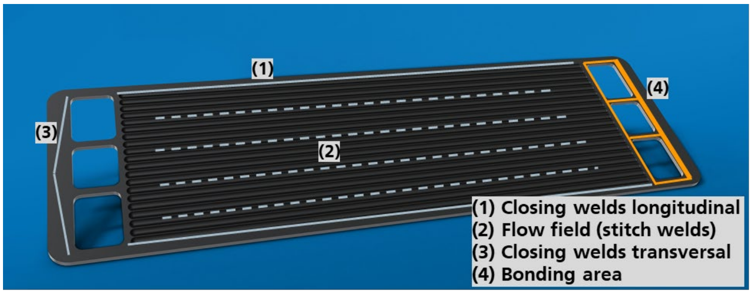

Fig. 4. Schematic demonstration of design aspects for weld seam location of a R2R capable BBP

4.2. Laser welding process set-up

The development of the welding process follows a new approach. In contrast to the state-of-the-art remote welding process, laser welding in the roll gap (laser roll welding) is to be realized in this development. The laser beam determines the welding position, while the welding feed movement is mainly generated by the strip movement. Fig. 3 displays the principle of the joining technology. The two half-shell strips are inserted into a rolling device for positioning and to ensure a zero gap during welding. The exact position of the two joining partners in relation to each other is defined by a pre-positioning unit at each strip. A single-mode laser beam is focused into this gap in the direction of strip travel by means of a fast scanner optics. By selectively positioning and switching on the laser beam in the joining gap, weld seams can be produced in the direction of strip travel (longitudinal seams). However, the superimposed scanning movement in the gap also enables transverse seams at a certain angle. Table 1 contains basic technical data of the welding set-up.

Table 1. Technical data of laser welding set-up

Technical data	Value
Laser source	Single-mode fiber laser
Wave length	1.070 nm
Spot size	∽ 40 µm
Laser power	Up to 2kW
Optics	2D high-speed galvo scanner
Rayleigh length	0,8 mm

4.3. Welding tests and results

All welding investigations are done at typical strip material of stainless steel grade 1.4404 in 100 µm thickness. For the validation of the welding process parameters carbon-coated material (outside) was used. Following development steps have been carried out within the basic work stage:

I. welding on flat strips for basic parameter detection in longitudinal and transversal direction
II. transfer to endless roll-formed strips for flow-field step-welds and longitudinal closure welds
III. technological analyses for the realization of real contours in combination of laser welding and bonding

The basic investigations were carried out under variation of the optical parameters and the essential welding parameters (e.g. beam power, spot geometry, travel speed, gap size and beam position). The basic technological parameters were determined and the weldability was demonstrated both in the pure longitudinal direction and with superimposed transverse movement of the beam. Following results have been determined (see also Fig. 5):

- longitudinal welding
    - stable process up to 30 m/min strip movement speed (= welding speed)
    - high quality of weld seams resulting from minimum gap size, self-guiding of the laser beam to the process zone in the gap
    - short stitch welds are producible by applying laser pulses
- transversal welds
    - can be realized with nominal welding speed of > 150 m/min (2.5 m/s) resulting from superposition of strip moving speed and scanner speed
    - seam quality and process stability are generally lower than longitudinal welds, depending on the precision of the beam position and the gap situation
    - real transverse seams cannot be produced, but welding is possible at an angle of at least 10° to transvers direction

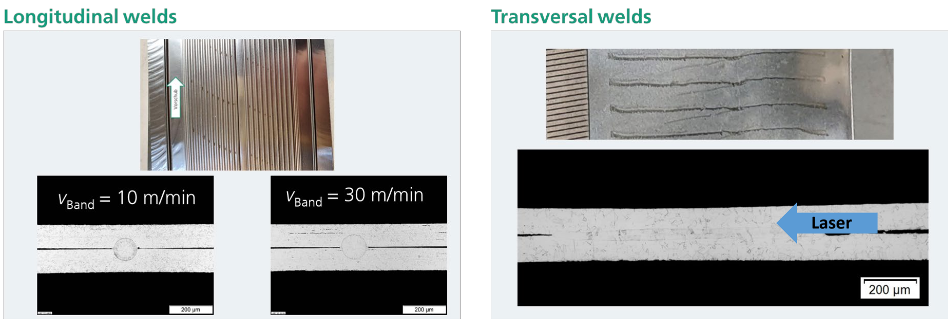

Fig. 5. Longitudinal weld at endless roll-formed strip samples and cross sections at 10 m/min and 30 m/min travel speed (left), transversal welds at flat strip samples and longitudinal cross section (right)

The cross sections show very small weld seams with stable shape and with low grade of imperfections. By adjusting the welding parameters, the seam geometry can be kept constant over a wide range of strip travel speeds (10 – 30 m/min). Especially remarkable is the very low thermal affection of the welded samples. Generally, no angle-distortion was detected (Fig. 5). Additionally, only minor degradation of the outer surface of the C-coated sheet was observed. The surface images show slight markings (Fig. 5), although no negative effects of the local surface modifications could be detected in corrosion tests.

In the next step, a process transfer was carried out on roll-formed test samples. The pressure rollers and positioning units were adapted according to the test contours to enable exact positioning of the top and bottom shells relative to each other. In this phase, the development of the stitch welds in the flow field took place. For this purpose, the individual stitches were welded by a pulse of a few milliseconds and then the scanner was used to move to the next welding position. The superimposition of transversal movement of laser beam and longitudinal strip movement results in a stepped welding figure (Fig. 5, top left). Fig. 6 shows a macro cross section of such a roll-formed and welded test sample. Potentially, this type of welding operation can also be carried out using several coordinated scanners. This also allows a combination of stitch welding in the flow field and seal welding on both sides.

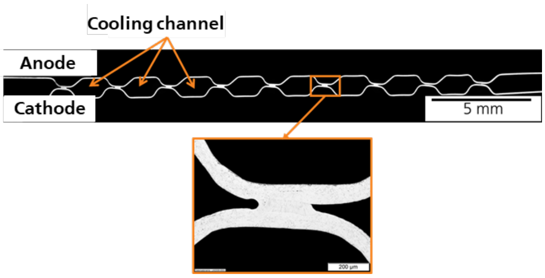

Fig. 6. Marco cross section of welded flow field sample with stitch welds

Typical weld defects occur particularly at the ends of the welds. These are usually shrinkage cavities resulting from solidification phenomena (Fig. 5 right).

5. Conclusion and outlook

The feasibility of a holistic process chain for R2R manufacturing of BPP is fundamentally proven by experimental investigations of single process steps. The processes coating, forming (hollow embossing rolling), laser welding and bonding as well as laser cutting were included in the considerations and developments. The set-up for laser roll welding of metallic strip-shaped bipolar plates is basically realized. Within the next development steps the set-up and welding technology will be improved by implementing additional optics in order to realize coordinated simultaneous welding and finally reach attractive low value of welding time.

The technical parameters achieved so far allow a possible strip speed of at least 30 m/min, which means that a total production output of the welding unit of approx. 1 BPP/s can be expected. In relation to the state of the art process (remote welding in overlap) the following positive effects can be expected for the R2R laser gap welding:

- higher production rate
- lower distortion (minimal penetration in gap welding vs. full penetration in overlap)
- no surface affection

In den welding operation, especially in transverse mode, physical welding speed values are reached, which are behind the conventional process limits of high-speed laser welding. The typical humping effects, which usually limit the process window in remote welding, are not observed in this way in the new roll welding process. Nevertheless, process technical aspects of this special welding configuration have to be investigated more in detail. Welding aspects are now being further elaborated in ongoing research and development projects. One focus is on combining laser welding in the gap with structural bonding. The main aim here is to minimize the heat input during joining and to minimize the production time.

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