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Fixture free laser beam welding for the automotive body shop

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Abstract

The current automotive body shop is dominated by resistance spot welding due to its low costs and robustness, especially regarding quality variations of the single parts. In contrast, laser beam welding is struggling to create a solid business case in big numbers despite its technological advancements like the welding speed. To economically resolve this issue, an approach is needed that creates a balanced synergy between both joining processes. BMW, together with the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) and the Institute for Machine Tools and Industrial Management (iwb) from the Technical University Munich, approached this challenge by developing a method to combine both welding processes through a lap-joint-flange integrated geometry, which can be installed off-tool in the press-shop. These functional geometries allow the advantages of resistance spot welding to be used to fix the geometry and create a laser-suitable gap situation without clamping tools for the following laser beam welding. Within this paper the technological and the financial viability of this method is proved, which is why this could be a major breakthrough for laser beam welding in the automotive industry.

Keywords: fixture free, resistance spot welding, laser beam welding, functional geometry, automotive production

1. Introduction

The automotive industry in general and the corresponding production systems are facing challenging times ahead. Currently, a technology shift can be observed from the combustion engine to the electric powertrain. The demand for mobility solutions is difficult to predict, especially during the K-shaped recovery from the COVID-19 pandemic (Dalten, et al. 2021) and the recent resource shortfalls are capable to completely halt production lines. To remain competitive facing such never seen before market fluctuations, a

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production system is necessary that is adaptable and robust. Especially the process chain for the painted automotive body, usually consisting of a highly automated press, body and paint shop, requires new approaches to achieve those ambitious goals. Due to the desired extremely high output, current production lines are often rigid (Hansen, Kampker and Triebs 2018). Remote laser beam welding (RLBW) is a highly promising welding technology to use in the automotive body shop production to conduce the needed flexibility. It has advantages like a relatively high welding velocity, it can weld a large number of materials, it is contactless thus geometry independent and it requires only an one-sided access to the welding zone. Despite those benefits it is only used as a niche technology in the modern automotive body shop. The dominant welding technology until today is resistance spot welding (RP). Although this welding process, in contrast to RLBW, requires access from both sides and the welding guns used are specific to the geometry of the parts to weld. Otherwise, RP is immensely robust against gap variations due to its action of force on the parts and the equipment costs are relatively low, especially for pneumatic weld guns.

One of the main obstacles for the use of RLBW is the hard to achieve positive business case in the body shop; starting from the high equipment costs due to the cost-intensive gap requirements up to the need to control the zinc gas evaporation during the welding of zinc coated steel. A lot of the described hurdles and the following costs occur when RLBW is only considered as a complete substitution technology to RP from the perspective of the product development without the huge impact on the production system in mind. The paper aims to change the view of RLBW in general. Away from the binary of either RP or RLBW towards a synergetic combination of both welding technologies in the proper sense for the automotive production system. The intent is to use the advantages of both welding technologies without the negative business by-effects and creating a synergy effect. In order to make this intent reality, a technological link between both welding technologies is required, but at the same time it must not create any negative business impacts on the production system. The chosen approach was to develop and test functional lap-joint-flange integrated geometries which are named BILS'M (shortcut from the German name "Bauteilintegrierte lasergerechte Spannmerkmale" – in English "Part-integrated laser-suitable clamping features"). In order to use BILS'M as envisioned, a fundamental understanding of the several new occurring effects is necessary. Based on a structured approach research and development was initiated by BMW, Fraunhofer and TUM.

2. State of the Art

2.1. Relevant characteristics of resistance spot and laser beam welding of zinc-coated steel

The modern automotive body shop consists of a wide variety of joining technologies due to the complexity of a modern automotive body, e.g., more than 10 different joining technologies can be seen in the body shop of the current BMW 7 Series. Which joining technology has to be applied depends heavily on the used materials for the parts to join. Besides steel and its different variations, a lot of innovative new materials became available during the last decades in the automotive industry, like aluminum, carbon fiber reinforced plastics or ultra high-tensile steels. With a wider material mix more joining technologies were needed. But besides all those advancements, steel remains the dominant material in the body shop till this day e.g., the current BMW 7 Series is made up of two thirds of steel. (Eroğlu, et al. 2019)

When welding steel sheets, an energy source is required to generate heat and create a common joint by first melting the materials of both partners in the geometrically defined adjacent joining zone, through which a permanent connection can be achieved after letting the created melt pool solidify (Schuler and Twrdek 2019). For RP the necessary heat is created through electric resistance initiated by two electrodes contacting the steel sheets and pressing them together to create a common joining zone. The result after releasing the sheets is a weld spot between both joining partners. Besides the geometrical parameters of the electrodes themselves the dominant process parameters are the amperage $\mathbf{I_S}$ and the pressure force $\mathbf{F_E}$ of the electrodes, as seen in Fig. 1. The pressure force varies typically around 3 to 7 kN, which is sufficient to close possible gaps due to manufacturing inaccuracies of up to a few millimeters if the material strength is not too high and the geometry of the welded module allows it. While producing a series of welding spots in a row, the average duration to create a weld spot is between 2 to 4 seconds, depending on the type of spot, the material thickness and coating and including approach, closing, welding and release of the weld guns.

The melting heat at RLBW is induced by the eponymous laser beam. The energy is transported by radiation thus no direct contact between the laser optics as the tool and the welding zone is necessary. The radiation is absorbed by the materials in the joining zone and creates a melt-pool. By moving the laser and the joining zone relative to each other, the melt pool follows the laser beam on the surface and creates a continuous weld seam. Because no force is induced the joining zone has to be geometrically completely prepared for the welding process; the gap between both partners should not be bigger than 0.3 mm. This tolerance zone can be expanded up to 0.8 mm (Müller, et al. 2014), if a modern laser optic system with an oscillation function is used. Besides the geometry in the joining zone the dominant parameters are the laser power P_L combined with the focus diameter d_L of the welding spot on the surface itself and the wavelength. In the automotive application within the body shop, the typical laser power range is between 3 and 6 kW and welding speeds of up to 6 m/min with upwards potentials. The weld can be executed in a lap or fillet configuration, the latter is visualized in Fig. 1 in an edge configuration. The edge makes automated detection for the correct position of the laser beam easier; the correct position is essential for a high-quality weld.

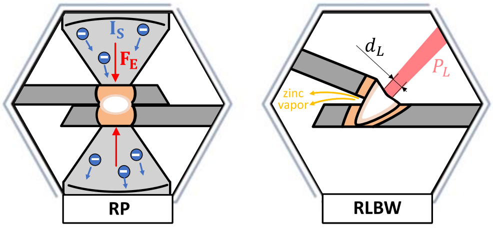

Fig. 1: BILS'M-relevant process characteristics of RP and RLBW (Source: Own interpretation of Schuler and Twrdek 2019)

Comparing RP and RLBW without the tangent needed preparations the RLBW is able to produce the required joint strengths between both parts much faster. A typical simplification to compare both welding processes strengths is a substitutional factor of 20 mm laser seam equals to a single resistance spot (Mei, et al. 2015). Consequently, RLBW is severely more productive than RP. Aside from the productivity advantage of RLBW a complication arises during the welding of zinc-coated steel. The zinc-coating itself is used as a relatively cheap method to protect the raw steel sheets from corrosion. If the coating should be penetrated, the remaining zinc is serving as a sacrificial cathodic protection. Though the zinc-coating is needed for the steel sheets, it is difficult to weld. Zinc has a boiling temperature of approximately 900 °C whereas steel has a melting temperature of approximately 1500 °C. This temperature deviation causes the zinc-vapor to be trapped in the lap between the sheets, if no other degassing option is provided. The result is a zinc-vapor eruption through the melt-pool causing spatters and destroying the continuity of the weld seam (Akhter, Steen and Watkins 1991). As it is a constant problem in the industry, a lot of fundamentals were examined to reduce the zinc-vapor eruptions, e.g., low-speed welding, creating laser humps before contacting both joining partners or even using multi-laser technologies (Ma, et al. 2012) . Some of them were more successful and industry-suitable than others, but all approaches aside from providing a real physical permanent evaporation path, like a gap or an opening, have shown a too narrow process window to be robust or cost-efficient enough for the body shop. (Kägeler 2013) An easy solution to create a degassing gap without the need of extra process steps is a clearing angle in an edge configuration. The open space lets the zinc vapor escape easily out of the process zone without any splatters, as shown in Fig. 1. RP welding on the other hand is able to deal with the zinc coating without the need for geometrical preparations only by adequately adapting the process parameters (Gedeon and Eagar 1986).

2.2. Impact of joining technologies on the automotive production system

The typical automotive body is a shell construction, even though new approaches are currently being investigated and even partly in use like casting or additive manufacturing, e.g., wire arc additive manufacturing. The motivation for the new approaches, among other things, is the demand for topology optimized structures, which will be useful for future lightweight requirements. (Pischinger and Seiffert 2016)

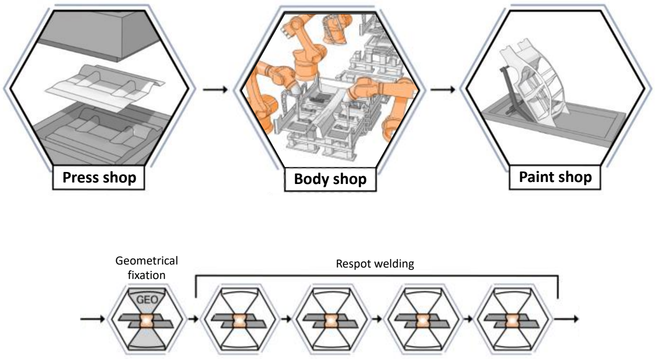

Fig. 2: Process chain for the painted automotive body with a focus on the RP in the body shop (Source: Own representation)

To produce the body as a shell construction it is necessary to manufacture the singular parts in the press shop, join them gradually to modules and at last to a dimensionally stable complete body in the body shop and ensure the corrosion resilience and tightness through a variety of procedures in the paint shop. This tripartite technological system, as depicted in Fig. 2, is highly interdepended and changes inside one technology may cause drastic effects in another. For example, reducing the amount of press steps and with it expanding the window of tolerance for the singular parts may cause the necessity for extra clamping fixtures in the body shop for a stable welding process and subsequently an instable welding process will lead to pores and spatters, which increases the efforts required in the paint shop. This example is especially important for the use of laser welding in a traditional product-oriented approach. Due to the higher demands regarding the part quality, the cost in the press shop increases as a result of more necessary press steps to achieve the desired narrow tolerance window. In the body shop RLBW-oriented clamping fixtures are needed to secure the laser suitable gap situation. The cost increase in comparison to an ordinary RP-suitable clamping fixture can rise by a factor of ten. Another cost intensifier for RLBW are the needed laser safety cells due to the immense laser powers. Last but not least the zinc-evaporation has to be controlled during the RLBW in order to avoid excessive costs in the body shop for reworking and sealing the possibly occurring open pores.

The use of RP has also its hurdles, especially the relatively low welding speed per spot in combination with a strictly paced production line which leads to an immense amount of required welding cells and robots. One cycle is usually not enough time to weld all needed spots, depending on the size of the module. The typical process is to first fix the geometry of module in a cell with a clamping fixture and after that only to respot the module without clamps in the following cells until all necessary spots are welded, as shown in Fig. 2. Based on the size and the needed weld spots, this can lead to respot lines of more than five cells in a row for a singular module. Each cell increasing the cost by containing industrial robots, the associated controllers and of course the geometry specific welding guns. On top of that the cells are occupying valuable space in the body shop. If a new body design has to be implemented in the same production line, every gun has to be checked for accessibility or new guns have to be added, further increasing the overall cost.

2.3. Functional geometries in the automotive body shop

An approach to join two metal parts without any additional elements like screws or bolts was discussed in Donhauser, et al. (2018). In that example the part-integrated features are serving a joining purpose by snapping one part into another through an intelligent springy geometry, as seen in Fig. 3. Another approach for part-integrated features is shown in Schlather, Oefele and Zaeh (2016), where part-integrated calottes in one part and apposite holes in the other part are used to orient them to each other without the need of a fixture. The calottes do not even need any additional steps in the press shop due to its off-tool manufacturable geometry. All those ideas have one thing in common, creating additional value for the production chain by simplifying following process steps and reducing costs; all without interfering with the product design itself from the view of the customer's point of view.

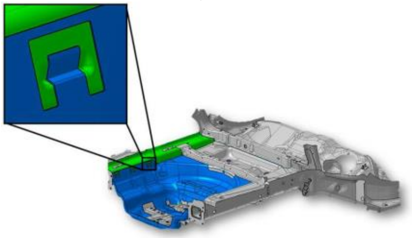

Fig. 3: Snapping elements to join two parts without further elements (Source: Donhauser, et al. 2018)

One approach to use part-integrated geometries for the benefit of RLBW is discussed in Bley, Weyand and Luft (2007). Even if technologically this approach is completely viable, it is either not cost-neutral compatible with the current shell constructions and general tolerances in the press shop e.g., see Fig. 4 left, or process restrictions and the positioning of the laser beam on the radius is not robust enough e.g., see Fig. 4 right.

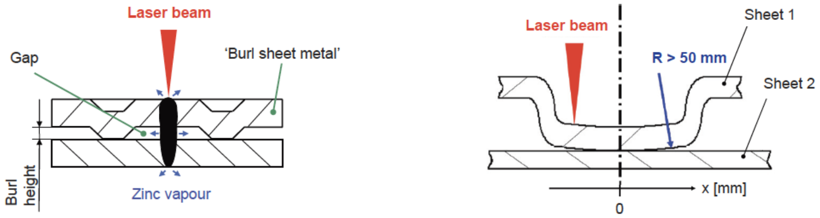

Fig. 4: Part-integrated geometries for the cost-efficient RLBW of zinc coated sheet metals (Source: Bley, Weyand and Luft 2007)

3. Development method of a lap-joint-flange integrated laser-suitable geometry (BILS'M)

Based on the current state of art and its economic ramifications for RLBW, as described in the previous chapter, we defined four postulates for the BILS'M technology (Safronov, et al. 2019), which have to be fulfilled during every step of the development and testing process:

1. RLBW is to be combined with a force-inducing joining technology, like RP for steel welding, through part-integrated functional geometries.
2. These geometries serve as the clamping method for RLBW, to make the usually required dedicated laser-suitable fixtures obsolete.
3. The gap configuration has to be ready for laser beam welding zinc-coated steel, hence a degassing option has to be integrated.
4. The use of BILS'M must never induce additional steps along the whole process chain; this means no extra steps are necessary in the press shops, as the geometries are created off-tool and the general tolerances are sufficient for the force inducing joining method are sufficient and no additional sealing is necessary in the paint shop.

Especially for laser beam welding zinc-coated steel those postulates are operating as a unified whole to hopefully create a positive business-impact on the production system. The chosen development method is based upon the well-known V-Model to make sure that every possible requirement was fulfilled and to synchronize the workload between the numerous stakeholders and involved parties. The V-Model method with the main focuses of activities for each phase is shown in Fig. 5.

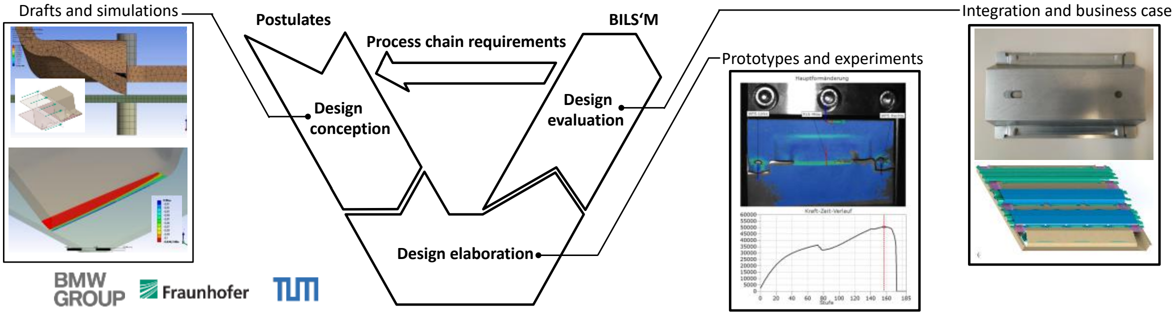

Fig. 5: Development method and the main activities during each development part (Source: Own interpretation of the V-Model)

Based on the defined postulates different geometries were drafted and permanently cross-checked with the stakeholders from the process chain. The most promising approaches were subject to extensive simulations. Besides the fundamental feasibility, the goal was also to understand if the typical general geometry tolerances in the press shop were sufficient for the general function but also acceptable as input for the two welding processes to come. In order to validate the resulting pressure force on the resistance electrodes during welding, a dedicated force measuring device was developed and built. Further, a testing method for the BILS'M geometry was developed to understand the achievable strengths but also the failure curves. The testing range varied between simple tensile tests under different angles up to complex analyzation with optical equipment to validate the simulation results, as seen in Fig. 5. Finally, the results were combined into design principles and dimensioning tools to be used to enhance possible future body design and validate the business case upon those.

4. Results and findings of the geometry development

Early in the development it became apparent, that two different geometries will be required to differentiate the two possible cases of application. One to enable drainage in the paint shop and one with an absolute tightness in the joining zone. For the dipping processes, like the cathodic coating, a lot of parts need options to drain the coating fluid. These openings are called cathodic beadings, as seen in Fig. 6, and are often found in the floor module of a body. The functional details of BILS'M are located in the RLBW-edge. This RLBW-edge is in its released state, so without the RP spots, clearly below the RP-edge in the z-direction. These intentional undersize guarantees, that after the force inducing RP-welding a direct contact between upper and lower sheet is present at the RLBW-edge and through the weld spots it is also fixed. The angle between lower and upper sheet guarantees that during the RLBW process the zinc is able to vaporize freely into the open backside. In conclusion a laser-suitable situation can be created without any laser-suited fixtures just by applying the standard RP process with its standard RP-suitable fixtures due to BILS'M.

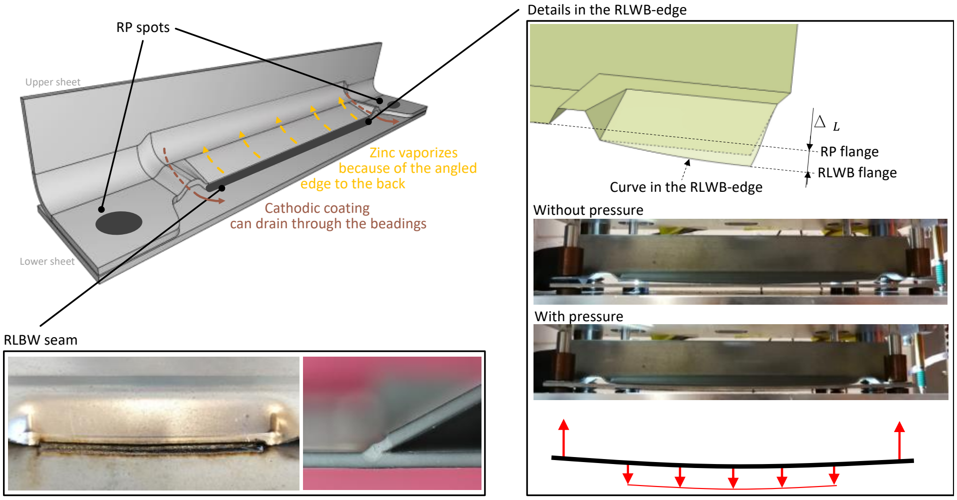

Fig. 6: The open BILS'M geometry in detail for allowing drainage in the paint shop (Source: Own representation)

If a weld zone has to be sealed against fluids, for example in the front, back or roof of the body, then often adhesives are used. Besides adding stiffness to the joint, it also seals the area between the flanges. For RP this adhesive is usually unproblematic, because first it is displaced by the induced force and the remaining adhesive in the joining zone simply burns through the heat. For RLBW, by contrast, a direct contact with adhesive in the joining zone drastically reduces the weld quality. The "closed" geometry to address adhesive in the flange is depicted in Fig. 7. Though adhesive is current state of the art in the body shop, it is obstructive to the effective dismantling capability. Adhesive makes it harder to detach the body cost-efficiently without mixing different materials with one another. In conclusion, other joining technologies are to favor in the future in terms of sustainability. (BMW Group 2021) Besides of those effects and because the closed geometry is still being tested, the further focus of this paper will be on the open one. The lookout based on the first test results of BILS'M with adhesive and the weldability is technologically promising.

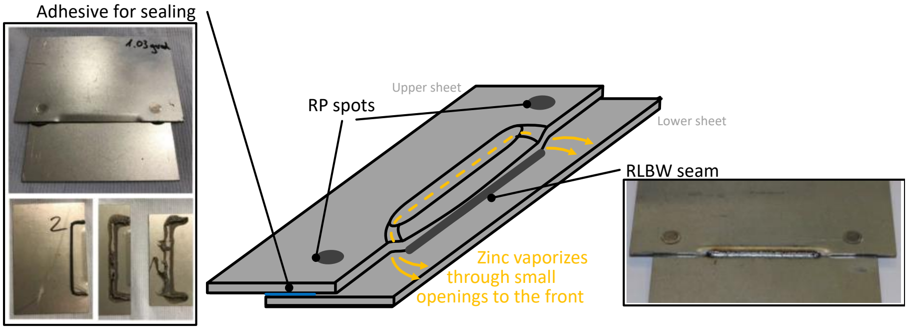

Fig. 7: Concept and first prototypes of the sealed BILS'M geometry (Source: Own representation)

The necessary force to close the resulting gap before RP welding is not allowed to exceed certain values to not endanger the stability of the RP process. The important geometric parameters influencing this force are the thickness and strength of both sheets and the total undersize z_L including the percentage of the curve. A sensitivity analysis showed that the length of the laser edge itself has a relatively low impact on the required force to close the gap. Experiments confirmed the simulation and stable laser welds of over 200 mm are possible without the need of a further fixture through BILS'M. To further validate the simulations, additional experiments were done by creating a special tool to press profiles like depicted in Fig. 8 with the option to control the important influencing parameters:

- The material was CR380LA, and thickness of the sheets was 1.2 mm, 2 mm and 2.5 mm
- The undersize varied between 0 mm and 3 mm in steps of 1 mm
- The laser edge length was tested with 58 mm (6 RP spots) und 180 mm (4 RP spots)

Next, all pressed profiles were controlled for their size accuracy and tested inside a device developed to measure the necessary forces at each welding spot. As the simulations predicted, the required force, even for the most difficult combination of 2.5 mm on 2.5 mm never exceeded the acceptable process window for the RP process.

Fig. 8: Concept of measuring the required forces to close the gap on the variable testing modules (Source: Own representation)

To investigate the resulting strength of RP and RLBW in one flange, a dedicated testing geometry was developed and used for sheer and peal stress. One concern was that the additional geometries in the flange would significantly change the failure curves. This could not be confirmed as the real results showed that the strength of both welds can be approximately added to get the resulting failure curve, as shown in Fig. 9.

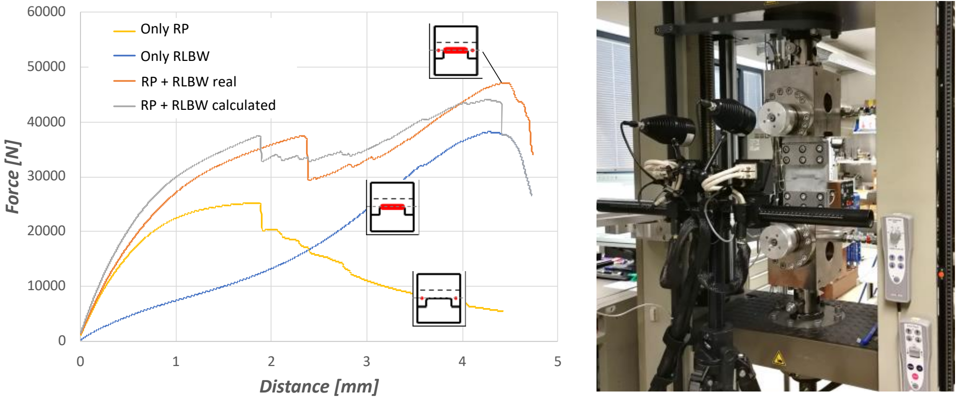

Fig. 9: Strength of the flange geometries of the two welding processes and their superposition (Source: Own representation)

5. Conclusion

The intent of the project was to design and evaluate a functional part-integrated geometry, referred to as BILS'M, based on the proposed postulates for the production system. The idea of BILS'M is to use RLBW for complete welding modules without the need for laser suitable fixtures. The research has shown that it was possible because of the intentional and angled undersize of the laser edge, which guarantees direct contact after RP welding and a chance for the zinc to freely vaporize during RLBW. Derived from the general tolerances for RP suitable parts in the press shop, a simulation and experimental validation was made to confirm the resulting forces required to close the gaps to be within the stable process windows for RP; meaning no additional costs are generated in the press shop. Besides the undersize, the thickness and material of the sheets also influence the resulting force. Further experiments are required to validate the limits of use, especially the maximum acceptable material strength and thickness for the sheets. For the typically used non-high-strength steels the viability of BILS’M could be confirmed. Another advantage was the ability to control the RLBW process better due to more stable inputs regarding the gap and zinc vaporization in contrast to an economical laser fixture. This means for example, instead of welding through a controlled weld into to lower sheet without damaging the zinc coating on the underside was repeatably possible. An issue from the aesthetic view is the deformation of the lower sheet, especially if it is significantly thinner as the upper sheet. In extreme configurations deformations in the z-direction of over 2 mm could be observed, resulting in visible small curves in the lower sheet. From the current point of development, it does not influence the general strength of the module and if it is located in an area not visible to the customer e.g., the floor module, it should be acceptable; presumed the curves do not collide with other elements of the car.

From the production systems view the use of BILS’M is enabling to reduce a lot of respot cells to only a few laser welding cells, like depicted in Fig. 10. This is possible thanks to the drastically higher welding speeds of RLBW compared to the equivalent of strength-input at RP welding. The business case gets better and better, the bigger the utilization of the RLBW cells is. This means postponing of the RLBW cells as far back as possible in the production lines is to favorize. For that the better accessibility of RLBW in contrast to RP welding is beneficial. Because of the numerous reductions of cells in general, a lot of space and with it a significant amount of equipment including the financial invest can be saved. Additionally, due to the reduced number of robots and attached RP welding guns, the energy consumption in general is reduced. The performance of the plant thanks to a lower time per unit increases and when new body models have to be integrated into the existing production lines, the necessary effort is tremendously lower with BILS’M. The reason for that is the material and geometric independence of the RLBW cells. With BILS’M no fixtures are necessary, and the laser can operate as flexible as a tool can gets. BILS’M lays the groundwork to combine the advantages of RP and RLBW welding cost efficient in terms of the production system.

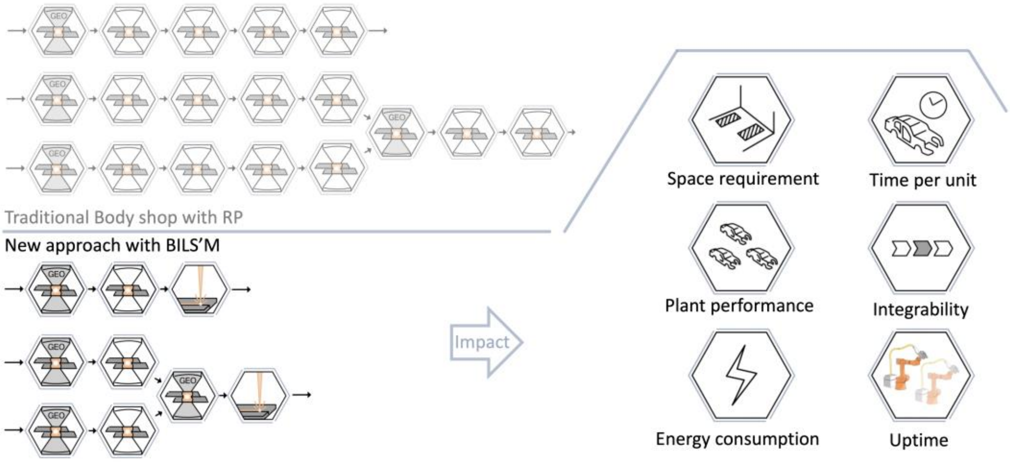

Fig. 10: Impact of BILS’M on the production system (Source: Own representation)

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