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A life cycle assessment of joining processes in the automotive industry, illustrated by the example of an EV battery case

Christian Brunner-Schwer[a,*], Josefine Lemke[a], Max Biegler[a], Tobias Schmolke[d], Sebastian Spohr[e], Gerson Meschut[d], Lutz Eckstein[e], Michael Rethmeier[c,b,a]

[a]*Fraunhofer Institute for Production Systems and Design Techology IPK, Pascalstraße 8-9, 10587, Berlin, Germany*
[b]*Bundesanstalt für Materialforschung und –prüfung, Unter den Eichen, 87 12205, Berlin, Germany*
[c]*Institute of Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587, Berlin, Germany*
[d]*Laboratory for material and joining technology (LWF), Paderborn University, Pohlweg 47-49, 33098 Paderborn, Germany*
[e]*Institute for Automotive Engineering (ika), RWTH Aachen University, Steinbachstraße 7, 52074 Aachen, Germany*

Abstract

Current ecological, economic and social changes are leading to a change in development, design and production of future vehicles. In this context, it is the stated goal of many manufacturers to advance the development of an environmentally friendly vehicle and climate-neutral production throughout the entire supply chain.

This study presents a comparative life cycle assessment of the joining processes laser beam welding, laser brazing and resistance spot welding. For this purpose, an approach tailored to welding processes is presented and applied to the example of a battery case for electric vehicles. For the welding process under consideration, the main influences on the resulting environmental impact categories are evaluated and compared. The requirements for ecologically efficient welding processes are discussed and outlined. The results show that particularly the materials involved, such as the consumption of the filler material, have the greatest environmental impact and thus offer the greatest potential for savings.

Keywords: life cycle assessment; laser beam welding; laser brazing; battery case;

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* Corresponding author. Tel.: +49 30 39006-399; fax: +49 30 3911037
E-mail address: christian.brunner-schwer@ipk.fraunhofer.de

1. Introduction

The stated goal of many automakers is to develop an environmentally friendly vehicle and achieve climate-neutral production throughout the supply chain. One approach to achieve these goals is to produce a battery case made exclusively of high-strength steels. Very high demands are placed on a battery case in terms of crash safety, leak tightness and package space. The massive energy storage units of electric vehicles (EVs), are integrated within a battery case in the underbody area of the vehicle structure. In order to be able to reduce the environmental impact during the production of such battery case, a process life cycle assessment (LCA) for five selected joining processes is carried out comparatively in this study, three laser-based joining processes and the hybrid resistance spot weld-bonding (RSW-Bonding) with two different adhesives. The joining processes are characterized by the fact that they are all capable of producing an airtight seam, which is required for an EV battery case.

1.1. Life cycle assessment

Life cycle assessment can be used to consider the environmental, social and economic impacts of a product or service over its entire life cycle [1]. From this definition and the need to assess environmental impacts, the LCA approach was developed. It is considered a tool for assessing the potential environmental impacts and resources consumed throughout the life cycle of a product. [2] The term product used in the definition includes both goods and services [3]. LCA is standardized in the ISO 14040 to ISO 14049 series and is a comprehensive assessment that considers all attributes or aspects of the natural environment, human health and resources [1]. In the early 1990s, the Society for Environmental Toxicology and Chemistry (Setac) began to standardise life cycle assessments and describe structures for the method [4]. Four central basic building blocks were defined, which were subsequently adopted in the ISO 14040 series of standards:

- Goal and Scope
- Inventory Analysis
- Impact Assessment
- Interpretation

This structure is the framework of an LCA and was thus also adopted in the LCA standard developed for welding processes, which was published for the first time in 2021. This standard, DIN/TS 35235, is the foundation for the calculations carried out in this work.

1.2. Life cycle impact assessment of joining processes.

The increasing number of publications on the further development of LCA and especially its application in the field of manufacturing technology reflects the growing interest in this topic. However, the number of publications explicitly examining welding processes in this context is still small. Mehta gives a general classification on energy demand, material waste, resources and parameters, environmental benefits and cost saving possibilities of different welding processes [5]. Kaierle et al. published in 2011 [6] a more detailed investigation of laser welding, including life cycle assessment methods. The work of Sproesser and Pittner [7–13] laid the groundwork in the mid-2010s for the explicit application of LCA to welding processes, with a focus on thick plate applications.

Pittner [14] documents an application of LCA explicitly to welding processes for thin sheets, as they are common in automotive construction. Resistance spot welding (RSW) and remote laser beam welding are compared, each for the welding of shear test specimens and for the welding of a cap profile made of galvanised sheet metal (1.0312). The shear test specimens are used for the ecological comparison of the selected welding processes, considering the mechanical-technological properties of the seams. For laser beam welding, the specified strength criterion is exceeded by 20 % for the selected seam length of 18 mm. This results in the potential to reduce the seam length accordingly, which contributes to a reduction in process time and the associated input flows, such as electrical energy and compressed air. Comparable to the studies by Sproesser et al. [9, 12], in which the material preparation for the welds have a significant influence on the impact categories, the influence of the material consumption caused by the overlap or the flange width is also more dominant in this study (up to 60 %) than efficiency improvements in energy consumption. Using the application scenario of the cap profile, it is shown that for laser beam welding, the total consumption of electrical energy decreases significantly when the downtimes of the laser are low. The calculated impact categories show the material consumption as the main influencing variable, followed by the electrical energy and the compressed air of the laser beam welding process. The other input and output variables, such as protective glasses (laser welding) and electrode caps (RSW), can be neglected, which significantly reduces the effort required to prepare the life cycle inventory and increases the applicability of life cycle assessment for welding applications as a standard design tool. [14]

Regarding the stand-by times of laser systems, Huang et al. [15] draw the same conclusion when analyzing CO_2 emissions of laser welding. Besides reducing stand-by times, if welding quality is maintained, increasing welding speed is the most important way to improve CO_2 efficiency. The reason for this is that the CO_2 emissions of the peripheral equipment in relation to the functional unit, e.g. the cooling system, can be significantly reduced by the shortened welding time. [15] The fact that peripheral equipment can significantly influence the overall assessment of an LCA is also shown by Epping et al. [16] with a comparison between manual and robotic welding. In a comparative LCA of arc processes, Sangwan et al. [17] state that the preparation of the life cycle inventory in terms of the consumption of resources such as electrical energy or filler materials is different for each process and recommends assessing the environmental impact for a specific welding process individually.

2. Methodology

2.1. Goal and scope

The aim of the life cycle assessment carried out is to assess the environmental impact of the joining processes described in a comparative manner. The study focuses exclusively on these processes and only includes inputs and outputs that are not identical between the five joining processes. It is expected that with the help of the calculated environmental impacts, a classification of the processes is also possible from an ecological perspective. The analysis of the joining processes covers the extraction of raw materials up to the point where the end product leaves the factory gate. According to Pittner [14] and Guinée [18], this cradle-to-gate approach is common when technology-oriented life cycle assessments are of interest.

The regional focus of the study is Germany. The structure of the life cycle impact assessment (LCIA) system is determined by the definition of the scope, which in turn is determined by an appropriate choice of system boundaries [14]. Fig. *1* shows the set system boundaries graphically for the chosen joining processes, following the work of Sproesser [7, 9, 10] and DIN/TS 35235.

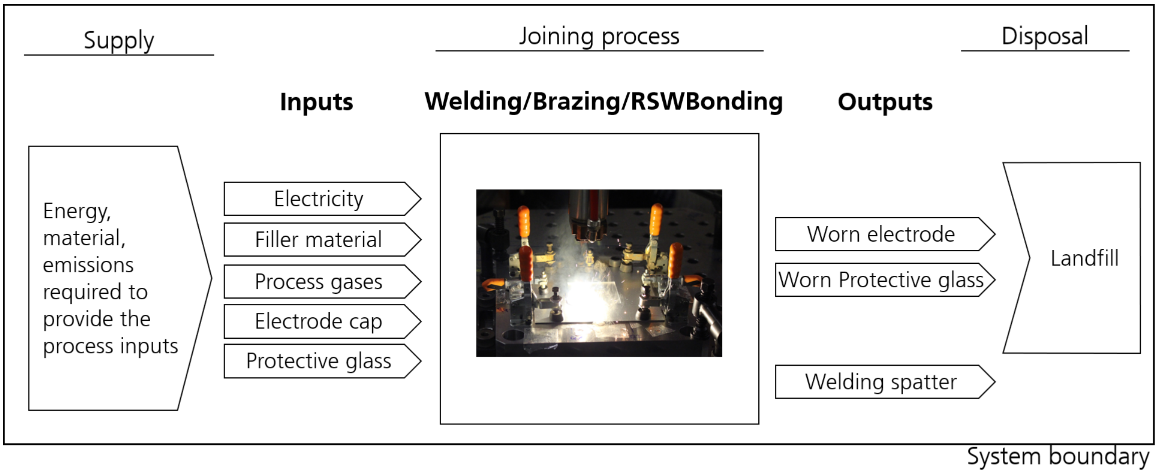

Fig. 1. Input and output flows as well as system boundary

2.2. Inventory analysis

For the comparative LCA, the weld seam of 1 m length is defined as a functional unit. To achieve the energy and material flow model of the study, primary data collected directly by the author and secondary data from literature and LCA databases are combined. The LCA database ecoinvent (version v.2.2 or version v.3.8) of the ecoinvent Association from Switzerland, adapted for the OpenLCA software, serves as the basis for the study. For the modelling of the processes and calculation of the potential environmental impacts, the OpenLCA software (version 1.11.0) is used.

The calculation procedure for the impact assessment follows the CML-IA Baseline Method developed by the Center of Environmental Science (CML) at Leiden University in the Netherlands. This method uses the problem-oriented midpoint approach and provides a list of mandatory impact categories. For this study, the following five impact categories or impact indicators are considered:

- Global warming (GWP100a)
- Eutrophication (EP)
- Photooxidants (POCP)
- Acidification (AP)
- Ozone layer depletion (OD)

The World 2000 database is used for the normalization and weighting sets. The choice of methods and indicators corresponds to the procedure of DIN/TS 35235.

The mix of electricity is assumed to be the mix of Germany. For the laser processes, compressed air is required for the optics, for which a consumption of 1800 l/min with 0.5 s pre-flow at 7 bar is assumed, comparable with [14]. For the wear of the protective glasses in the laser processes, a weight of 96 g and a change every 2 weeks is assumed, as in [14], assuming a production scenario of 6 days/week, 8 hours welding time/day. Transport, weld spatter and welding fumes are not considered.

Table 1. Life Cycle Inventory for one meter of weld seam

Parameter	Unit	Laser remote welding	Laser welding with filler metal	Laser brazing	Resistance spot weld-bonding*
Process time	s/m	15	20	20	7.6
Electric power sum	Wh/m	147.3	162.78	152.45	66.67
-- Laser / C-Gun	Wh/m	96.88	95.58	85.25	22.0
-- Robot	Wh/m	5.42	7.2	7.2	41.0
-- Chiller	Wh/m	45.0	60.0	60.0	3.0
Filler material	g/m	-	6.8	16.00	17.5
Compressed air	l/m	465	615	615	-
Protective glass	mg/m	4.17	5.56	5.56	-
Electrode caps	mg/m	-	-	-	840

* two different adhesives are being investigated for this process

2.2.1. *Laser remote welding*

A 6 kW disk laser with a wavelength of 1030 nm is used for the laser welded samples. The welds are carried out as remote welds with remote welding optics model RLW-A from Scansonic MI GmbH and an imaging scale of 1:2.9 with a fiber diameter of 200 µm. The optics are inclined 15 degrees laterally to the fillet weld and are stationary during welding. The welding parameters are documented in Table 2.

Table 2. Process parameters for the laser welding processes

Parameter	Laser remote welding	Laser welding with filler metal	Laser brazing
Laser power in kW	5	3.7	3.3
Feed rate in m/min	4.0	3.0	3.0
Wire feed rate	-	3.3	3.0

2.2.2. *Laser welding with filler metal*

For laser welding with filler metal, the same beam source, handling system and cooling system are used as for laser remote welding. The process parameters are summarized in Table 2. The optics used is an ALO4 with tactile wire feed from Scansonic MI GmbH. The welding wire used is a 1.0 mm G3Si1 wire, which is assumed to be steel wire from the World Steel Association database [19] with a density of 7.85 g/cm^3 in the LCA.

2.2.3. *Laser brazing*

For laser brazing, the same beam source, handling system and cooling system are used as for laser remote welding. The process parameters are summarized in Table 2. The optics used is an ALO4 with tactile wire feed from Scansonic MI GmbH. The brazing wire used is a 1.2 mm CuSi3 wire, which is assumed to be pure copper wire with a density of 8.5 g/cm^3 in the LCA.

2.2.4. Resistance spot weld-bonding

Resistance spot weld-bonding combines conventional RSW with an adhesive bonding process so that a gas-tight joint can be created. The adhesive used is a two-component EP (2K) and a one-component EP (1K). This adhesive is developed for use in structural joints with high toughness and strength. It has high heat and environmental resistance and can also be used in hybrid joints such as joints combined with RSW and riveting. For the consideration of the environmental impact of the analysed adhesive, the values for each impact indicator are directly considered in the model based on the corresponding European Environmental Product Declaration. For this purpose, the data published by the Association of the European Adhesive and Sealant Industry (FEICA) on products based on epoxy-resin, group 1 and 2 as per ISO 14025 and EN 15804+A2 and relevant system boundary A1-A3 with a density of 1.2 g/cm^3 are used [20]. The ideal adhesive volume is assumed to be 4.8 cm^3 multiplied by the safety factor of 3. For the wear of the electrode caps during RSW bonding, a weight of 2 x 21 g and a service life of 1000 spots is assumed, as for [14], with a waste recycling rate of 50 %.

Table 3. Process parameters for resistance spot weld-bonding

	Welding current in kA	Adhesive consumption in g/m	Spots per meter seam	Electrode force in kN	Pre and post hold times in ms	Welding time in ms	Cooling-on time in ms
Resistance spot weld-bonding	7.1	17.5	20	4.5	600	380	230

3. Results and discussion

3.1. Impact assessment

Fig. 2 summarizes the results of the impact assessment of all five joining processes on the basis of the defined impact categories.

- Global warming (GWP)

The impact category GWP is the category that considers effects of anthropogenic emissions on the radiation budget of the atmosphere. The impact assessment shows that for the five joining processes studied, emissions range between 0.11 kg CO_2 eq. to 0.29 kg CO_2 eq. for one meter of weld. For the laser-based joining processes, the consumption of electrical energy has the greatest environmental impact and for RSW bonding it is the adhesive, i.e. the filler material. In addition, it can be determined that for the laser-based joining processes, the consumption of compressed air, at 31 % - 33 %, causes a third of the emissions. The wear of protective glasses in the laser-based processes and the wear of electrode caps in the RSW process are negligible.

- Eutrophication (EP)

The impact assessment for the impact category eutrophication is between $3.84 \cdot 10^{-4}$ kg PO^{3-4} eq. and $3.52 \cdot 10^{-4}$ kg PO^{3-4} eq.. The production of copper wire for laser brazing leads to eutrophication that is about six times higher than for the other joining processes.

- Photooxidants (POCP)

The impact assessment for the impact category of photooxidants considers the formation of ground-level chemical compounds such as ozone through the reaction of air pollutants (e.g. NOx) with solar radiation. Here, the emission values are between $5.06 \cdot 10^{-6}$ kg C_2H_4 eq. to $6.58 \cdot 10^{-5}$ kg C_2H_4 eq.. Again, copper production for the laser brazing process is the dominant emitter.

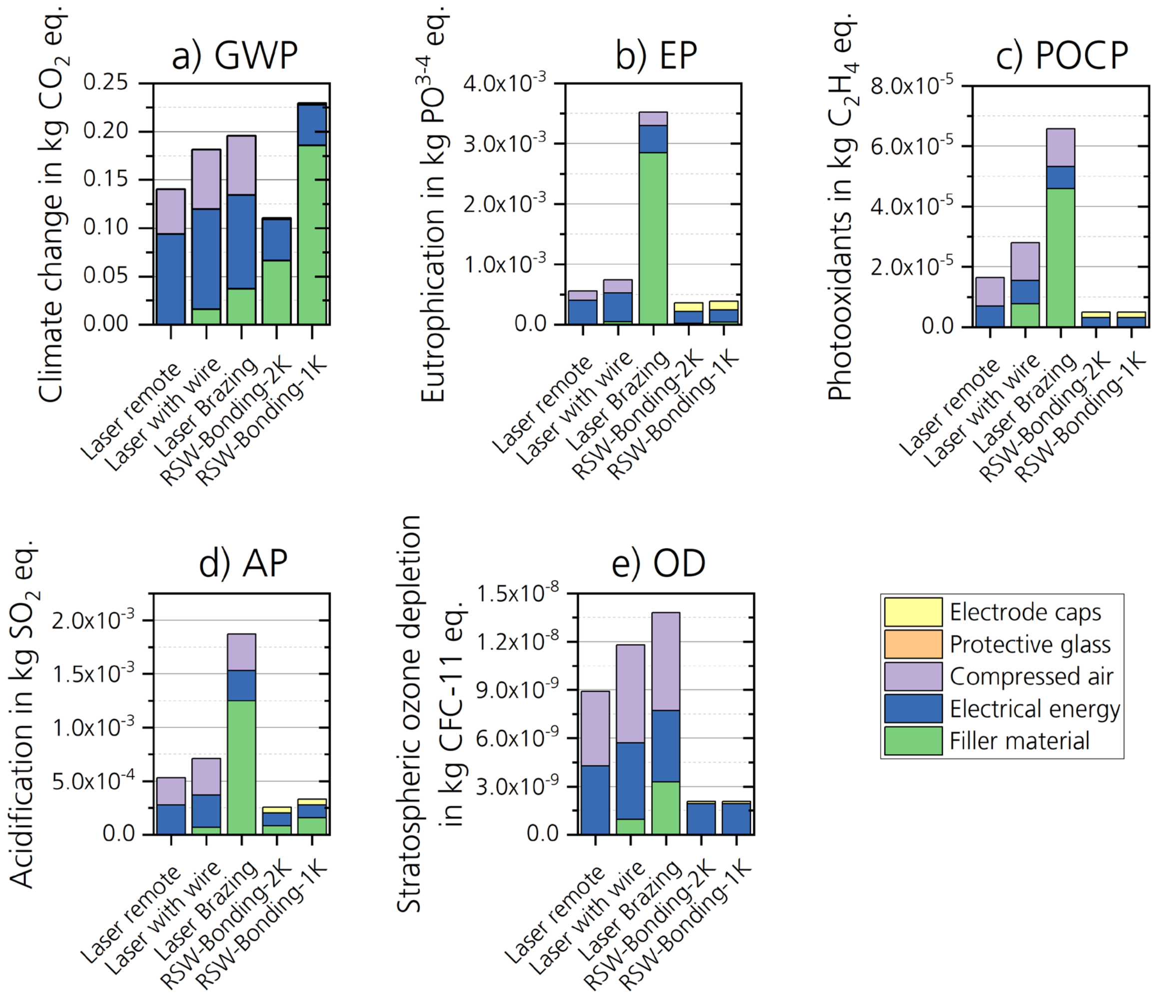

Fig. 2. Results of the impact assessment

- Acidification (AP)

The impact assessment for the impact category of acidification considers the generation of acid-forming pollutants with effects on soil, groundwater, organisms and the ecosystem. Here the emission values are between $2.54 \cdot 10^{-4}$ kg SO_2 eq. to $1.87 \cdot 10^{-3}$ kg SO_2 eq.. Again, copper production for the laser brazing process is the dominant emitter and results in an environmental impact of $1.87 \cdot 10^{-3}$ kg SO_2 eq. for the laser brazing process.

- Ozone layer depletion (OD)

The impact assessment for the impact category of stratospheric ozone depletion considers the effect of ozone layer depletion due to anthropogenic emissions. The emission values range from $2.08 \cdot 10^{-9}$ kg CFC-11 eq. to $1.38 \cdot 10^{-8}$ kg CFC-11 eq.. In particular, the production of compressed air and the electricity required are significant emitters.

3.2. Interpretation

Firstly, it can be stated that the emissions of the considered joining processes for the impact categories eutrophication (EP), photooxidants (POCP), acidification (AP) and ozone layer depletion (OD) are at a very low level. The level is comparable to the results for these categories from Pittner [14]. For the impact categories EP, POCP and AP, the filler metal for the laser brazing process is the dominant factor for the environmental impact. In the EP, POCP AP and OD impact categories, the order of the five processes in terms of the magnitude of the environmental impacts is consistent, with the laser brazing process as the process with the greatest impact and the RSW processes with the least impact.

The impact category GWP is the category that is also the most important for industry and regulatory institutions. The calculated values 0.11 kg CO_2 eq. to 0.29 kg CO_2 eq. are to be interpreted as emissions per meter of joined seam and thus scalable for any component, such as the investigated battery box of an EV. This also applies to the remaining impact categories. Due to the described calculation method, the share of compressed air and required electrical energy is almost identical for the laser processes, with 0.159 kg CO_2 eq. for laser brazing, 0.165 kg CO_2 eq. for laser wire welding and 0.14 kg CO_2 eq. for laser remote welding. Laser remote welding requires the highest laser power, but also has the shortest welding time for one meter of weld due to the comparatively high feed rate of 4 m/min. This is consistent with Huang's findings [15] that the GWP-efficiency of laser welding increases with increasing laser power and feed rate. For the processes of laser welding with wire and laser brazing, the emissions for the filler metal must be added, so that laser remote welding has the lowest GWP emissions compared to these processes. The calculations for laser remote welding can be compared with Pittner's study [14] in which a 1-meter cap profile is analyzed. However, Pittner also takes the emissions of the required base material into account. Without the base material, Pittner states GWP emissions of about 0.05 kg CO_2 eq., which are about three times lower than those of laser remote welding in this study. This could be due to the fact that the cap profile examined by Pittner is welded with stitch welds, i.e. a sequence of many short seams (18 mm) to join the component of one meter in length. The calculation presented here, however, assumes a completely continuous seam of one meter in length.

The RSW-Bonding processes differ only in the GWP emissions for the filler material (adhesive). The adhesive is so impactful that the RSW-Bonding process with the 2k adhesive has the lowest GWP environmental impact compared to all other joining processes and at the same time the RSW-Bonding process with the 1k adhesive is the process with the highest environmental impact. It is important to emphasize here that the respective environmental impacts depend solely on the classification of the adhesives into the respective EPD groups. In this case, the classification was made by the adhesive manufacturer himself.

In summary, the RSW-Bonding process is an environmentally friendly method of joining a component in a gas-tight manner if the lowest possible environmental impact can be considered when selecting the adhesive. An alternative to this can be a laser-based joining process. In particular, the laser wire welding process is a process that enables good seam tightness and promises low environmental impact.

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References

[1] Robberts, J. and Levy, M. How to Know If and When Its Time to Commission a Life Cycle Assessment. 2020.

[2] Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., and Suh, S. Recent developments in Life Cycle Assessment. In: Journal of environmental management, 1. 2009, S.1–21.

[3] Deutsches Institut für Normung. 2021. Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (ISO 14040:2006 + Amd 1:2020); Deutsche Fassung EN ISO 14040:2006 + A1:2020 13.020.10, 13.020.60. Beuth Verlag GmbH, Berlin 13.020.10, 13.020.60, 14040.

[4] 1993. Guidelines for Life-Cycle Assessment: A 'Code of Practice'. From the workshop held at Sesimbra, Portugal, 31 March - 3 April 1993. Edition 1 1.

[5] Mehta, K. P. 2019. Sustainability in Welding and Processing. In *Innovations in Manufacturing for Sustainability*, K. Gupta, Ed. Materials Forming, Machining and Tribology Ser. Springer, Cham, S.125–145.

[6] Kaierle, S., Dahmen, M., and Güdükkurt, O. 2011. Eco-efficiency of laser welding applications. In *SPIE Eco-Photonics 2011: Sustainable Design, Manufacturing, and Engineering Workforce Education for a Green Future*. SPIE Proceedings. SPIE, S.80650T.

[7] Chang, Y.-J., Sproesser, G., Neugebauer, S., Wolf, K., Scheumann, R., Pittner, A., Rethmeier, M., and Finkbeiner, M. Environmental and Social Life Cycle Assessment of Welding Technologies. In: Procedia CIRP. 2015, S.293–298.

[8] Sproesser, G., Chang, Y.-J., Pittner, A., Finkbeiner, M., and Rethmeier, M. Life Cycle Assessment of welding technologies for thick metal plate welds. In: Journal of Cleaner Production. 2015, S.46–53.

[9] Sproesser, G., Chang, Y.-J., Pittner, A., Finkbeiner, M., and Rethmeier, M. Environmental energy efficiency of single wire and tandem gas metal arc welding. In: Welding in the World, 4. 2017, S.733–743.

[10] Sproesser, G., Chang, Y.-J., Pittner, A., Finkbeiner, M., and Rethmeier, M. 2017. Sustainable technologies for thick metal plate welding. In *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives*, R. Stark, G. Seliger and J. Bonvoisin, Eds. Springer Nature, Cham, S.71–84.

[11] Sproesser, G., Pittner, A., and Rethmeier, M. Increasing Performance and Energy Efficiency of Gas Metal Arc Welding by a High Power Tandem Process. In: Procedia CIRP. 2016, S.642–647.

[12] Sproesser, G., Schenker, S., Pittner, A., Borndörfer, R., Rethmeier, M., Chang, Y.-J., and Finkbeiner, M. Sustainable Welding Process Selection Based on Weight Space Partitions. In: Procedia CIRP. 2016, S.127–132.

[13] Ward, H., Burger, M., Chang, Y.-J., Fürstmann, P., Neugebauer, S., Radebach, A., Sproesser, G., Pittner, A., Rethmeier, M., Uhlmann, E., and Steckel, J. C. Assessing carbon dioxide emission reduction potentials of improved manufacturing processes using multiregional input output frameworks. In: Journal of Cleaner Production. 2017, S.154–165.

[14] Pittner, A. and Rethmeier, M. Life Cycle Assessment of Fusion Welding Processes—A Case Study of Resistance Spot Welding Versus Laser Beam Welding. In: Advanced Engineering Materials, 6. 2022, S.1–14.

[15] Huang, Z., Cao, H., Zeng, D., Ge, W., and Duan, C. A carbon efficiency approach for laser welding environmental performance assessment and the process parameters decision-making. In: The International Journal of Advanced Manufacturing Technology, 7-8. 2021, S.2433–2446.

[16] Epping, K. and Zhang, H. A Sustainable Decision-Making Framework for Transitioning to Robotic Welding for Small and Medium Manufacturers. In: Sustainability, 10. 2018, S.1–18.

[17] Sangwan, K. S., Herrmann, C., Egede, P., Bhakar, V., and Singer, J. Life Cycle Assessment of Arc Welding and Gas Welding Processes. In: Procedia CIRP. 2016, S.62–67.

[18] Guinée, J. Handbook on life cycle assessment — operational guide to the ISO standards. In: The International Journal of Life Cycle Assessment, 5. 2001.

[19] World Steel Association. Life cycle assessment methodology report. World Steel Association, Brussels. 2011.

[20] Institut Bauen und Umwelt e.V. Environmental Product Declaration DBC, EFCC, FEICA, IVK – Products based on epoxy-resin, group 2. 2022.