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ORIGINAL ARTICLE

Energy efficiency and environmental impacts of high power gas metal arc welding

Gunther Sproesser[1] · **Ya-Ju Chang**[3] · **Andreas Pittner**[2] · **Matthias Finkbeiner**[3] · **Michael Rethmeier**[1,2]

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Abstract Single-wire gas metal arc welding (SGMAW) and high power tandem GMAW (TGMAW) are evaluated with respect to energy efficiency. The key performance indicator electrical deposition efficiency is applied to reflect the energy efficiency of GMAW in different material transfer modes. Additionally, the wall-plug efficiency of the equipment is determined in order to identify the overall energy consumption. The results show that energy efficiency can be increased by 24 % and welding time is reduced over 50 % by application of the tandem processes. A comparative life cycle assessment of a 30-mm-thick weld is conducted to investigate the influences of the energy efficiency on the environmental impacts. The environmental impacts on the categories global warming potential, acidification potential, eutrophication potential, and photochemical ozone creation potential can be reduced up to 11 % using an energy-efficient TGMAW process.

Keywords Life cycle assessment (LCA) · Energy efficiency · High power welding · Tandem gas metal arc welding

✉ Gunther Sproesser
gunther.sproesser@gmail.com

[1] Institute of Machine Tools and Factory Management, Technische Universität Berlin, Pascalstr. 8-9, 10587 Berlin, Germany

[2] Department of Component Safety, Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany

[3] Department of Environmental Technology, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

1 Introduction

Sustainable development and climate change mitigation both demand for resource-efficient production [16, 42]. Previous studies by Sproesser [35] and Chang [6] have shown that apart from filler material, electricity consumption dominates the environmental burdens of gas metal arc welding (GMAW). However, energy consumption of the GMAW processes currently has been treated with minor attention by the industry as stated by Kim [21], Aso and Cheung [1], and the OECD [24]. This is mainly due to the focus on economic process performance (e.g., welding speed), which has been intensively pushed forward in the lastecades.

Typically, an economically efficient GMAW process is executed in the spray arc and pulsed arc operation mode. Further increase of productivity can be achieved by applying a tandem GMAW (TGMAW) process, which reaches significantly higher deposition rates and welding speeds. TGMAW can be operated with various types of material transfer. The most widespread configuration is the pulsed arc on both electrodes. Especially for the common welding gun designs, anti-phase (alternating) pulses are used by Ueyama [41], Larkin [23], Pan [25] and Thompson [37] in order to prevent arc disturbances. Alternative synchronization patterns like in-phase, phase shifted, or even independently controlled (asynchronous) pulses have also been performed stable conditions by Ueyama [39, 40] and Sproesser [36]. In [45], Xiang applies a third wire between the electrodes to prevent process instabilities from in-phase pulses. Besides the pulsed operation mode, spray arc and short arc transfer was successfully applied by Thompson [37] and Hedegard [14] but was limited to a specific welding gun configuration. Another process variant for GMAW and TGAMW is the energy reduced dip transfer with a cyclic motion of the electrodes (ED transfer), which is elaborated in Trommer [38] and Kah [20].

Energy consumption is closely related to the energy flows of the arc process that are described in detail in literature [3, 5, 8, 12, 13, 18, 27]. Among all efficiency indicators presented, the effective efficiency has the strongest influence on the energy consumption of GMAW. This is because it determines the relative amount of energy with respect to the arc power used for melting the wire and the base material. Generally, the effective efficiency decreases with increasing process powers as stated by Pépe [27] and Hälsig [13]. Bosworth [3] found that for the same deposition rate, pulsed instead of non-pulsed welding demanded a lower process power, which favors pulsed welding in terms of energy efficiency. Hälsig [13] observed a higher effective efficiency for TGMAW in contrast to single-wire GMAW (SGMAW) with a spray arc at high deposition rates and thus signified an increased energy efficiency of TGMAW. However, Pépe [27] and Hälsig [12] discovered that for several GMAW processes, the needed process power for a certain material deposition rate varies significantly despite having similar effective efficiencies. Consequently, the effective efficiency does not serve as an exclusive measure for energy efficiency and the absolute process power demand for a desired output has to be taken into account. Additionally, effective efficiency of high power GMAW above a deposition rate of 8 kg/h has been exclusively investigated by Hälsig with 12 kg/h [13].

Another indicator apart from the effective efficiency was studied by Chandel [5] for SGMAW with a spray arc. The investigated electrode melting efficiency determines the amount of molten filler material relative to the theoretical amount that could be molten with the energy calculated with the arc voltage and current. It was shown that more filler material can be molten per unit of process power when welding with higher currents. Thus, results suggest applying high welding powers in order to promote a relatively lower energy demand for melting the wire.

First and recent works with reference to the energy consumption of GMAW were done by Hübner [15] and Sproesser [36]. Hübner et al. [15] were using a third wire in a TGMAW process to reduce the burn-off rate of alloying elements and to stabilize the process. Stated energy efficiencies are between 594 g/kWh for a TGMAW process with anti-phase pulses and 833 g/kWh for the three-wire process. However, the publication lacks of a formal definition of the energy efficiency indicator. Sproesser et al. [36] were formulating the electrical deposition efficiency (EDE) for GMAW followed by a study on a SGMAW process with a spray arc and a TGMAW process with asynchronous pulsed arcs. The formulation of the EDE expresses energy efficiency via the measured energy consumption of the arc process with respect to the molten filler material. Consequently, the EDE is expressed in grams per kilowatt-hour. The results of Sproesser et al. [36] showed high potentials for energy efficiency with the TGMAW process exceeding the values for a pure tandem process presented by Hübner [15]. However, the studies cover only a limited range of deposition rates that has to be enlarged for a comprehensive characterization of the energy efficiency.

To evaluate the environmental impacts of a process or product, life cycle assessment (LCA) is applied as the state-of-the-art methodology [9, 10, 17]. It is an ISO-standardized methodology in evaluating environmental burden on process or product levels from a cradle-to-grave perspective and also in preventing burden shifting from different life cycle phases [11]. The application of LCA on the process level of manufacturing has already been performed in order to compare environmental impacts of different technologies and process parameters, e.g., by Herrmann [43], Bourhis [4], and Pusavec [29]. LCA has been applied for comparing different welding technologies. For example, Shrivastava [34] compared the environmental impacts of GMAW and friction stir welding to join aluminum sheets with regard to the categories climate change, acidification, eutrophication, ecotoxicity, and stratospheric ozone depletion by using the TRACI methodology. Studies focusing on GMAW of low-alloyed steels were conducted by Zukauskaite [46], Drakopoulus [7], and Sproesser [35]. Zukauskaite [46] compared flux cored GMAW, submerged arc welding (SAW), and manual metal arc welding (MMAW) applied for thick metal plates. The results indicated that SAW is the most environmentally friendly process predominantly because of its lower fume generation in contrast to GMAW. Drakopoulos [7] came to the same conclusion and favored SAW for welding in ship hull repair. In their papers, materials, electricity, fumes, generated heat, and shielding gas for MMAW, SAW, and flux-cored GMAW were considered and assessed by using the impact assessment methods Eco-Indicator 99 and EPS 2000. An analysis of GMAW with solid wires, hybrid laser arc welding, and manual metal arc welding for a 20-mm-thick butt joint was presented by Sproesser [35]. The impact assessment results showed that the filler material and the consumed energy dominate the environmental burdens of GMAW in climate change, acidification, eutrophication, and photochemical ozone creation. As a consequence, welding with higher energy efficiency would reduce the environmental impacts significantly but has not yet been investigated on a quantitative level.

To sum up, the energy flows in GMAW and TGMAW with respect to the arc power have been intensively studied before describing the influences of the different material transfer modes and process parameters. However, most of the work focused on relative factors regarding the arc power and did not address the absolute amount of consumed energy.

Especially, the quantitative relation between the energy efficiency of a process and the corresponding environmental impacts of the produced weld has not been under investigation yet.

Hence, this paper aims at evaluating the energy efficiency, expressed by the EDE, and the environmental impacts of SGMAW and TGMAW. SGMAW with a spray arc and a pulsed arc transfer and TGMAW with alternating pulsed arcs, asynchronous pulsed arcs, and the ED transfer are under survey. Moreover, a comparative LCA of SGMAW with a spray arc and TGMAW with asynchronous pulsed arcs for a 30-mm-thick butt joint is conducted to investigate the influences of energy efficiency on the environmental burdens. On the one hand, the results support industry with data for eco-efficient process selection and development. On the other hand, it states how process performance, energy efficiency, and environmental impacts can be improved at the same time.

2 Methodology

2.1 Determination of energy efficiency

Energy consumption was assessed by power measurements at two positions, namely power supply measurement and process power measurement. As shown in Fig. 1, current and voltage are measured before and after the welding power source. The power supply measurement evaluates the total power P_S excluding the welding robot and including secondary consumptions of the welding power source, e.g., from the wire feeder. P_S is used to calculate the wall-plug efficiency of the equipment and to determine the overall energy consumption. A commercial measurement system was applied to measure and record current and voltage of the three phases separately between the power supply and the welding power sources. P_S was calculated according to Eq. 1 by the sum of the effective powers of each of the three phases. P_{s1} ,P_{s2}, and P_{s3} were provided directly by the measurement system.

$$P_S = P_{s1} + P_{s2} + P_{s3} \tag{1}$$

The process power P_W quantifies the energy that is needed by the process to create the weld pool and to melt the wire. P_W enables investigation of the process parameters and provides information about the stability of the process. Furthermore, disturbances from the equipment (e.g., chiller, inner circuit power) can be excluded. Current I and voltage U were measured and recorded with a commercial data acquisition system. As recommended in [3, 30], P_W is calculated by applying the arithmetic mean value of the instantaneous power shown in Eq. 2. The wall-plug efficiency of the equipment η is calculated by Eq. 3.

$$P_W = \frac{1}{t}\int_0^t U \cdot I dt \tag{2}$$

$$\eta = \frac{P_W}{P_S} \tag{3}$$

The EDE serves as a key performance indicator for the energy efficiency of a GMAW process in this study. It is stated in Eq. 4 by using the process parameters wire feed rate wfr, process power P_W, the wire electrode cross-section area A_W, and the density of the filler material ρ.

$$EDE = \frac{wfr}{P_W} \cdot \rho \cdot A_W \text{ in g/kWh} \tag{4}$$

The indicator EDE is mainly affected by the absolute process power that is needed for a set wire feed rate. In contrast to the effective efficiency, the EDE is an absolute quantity that is directly related to the energy consumption. Consequently, the required energy for a given weld can be calculated. The determination of the absolute electricity consumption E for a weld of the mass m is shown in Eq. 5 by applying the wall-plug efficiency η.

$$E = \frac{m}{EDE \cdot \eta} \text{inkWh} \tag{5}$$

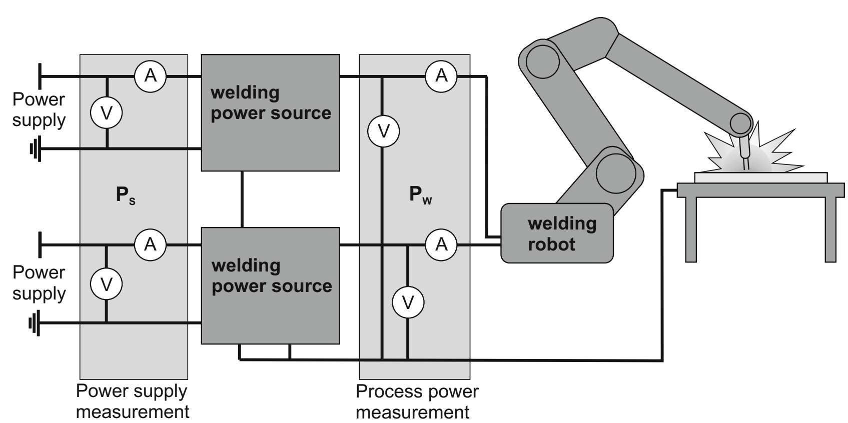

Fig. 1 Schematic diagram of the power measurement system

2.2 Energy efficiency investigations

Welding was performed automatically in the flat position by a welding robot. Welding samples were made of structural steel grade S355J2+N (DIN EN 10025-2). The 30-mm-thick steel plates had a length of 400 mm and a width of 200 mm. The V-grooved specimens with a 50° opening angle were tack welded beforehand and prepared with a ceramic backing plate. The filler material was a standard wire G4Si1 (DIN EN ISO 14341) with a diameter of 1.2 mm. The data was measured under real welding conditions by filling the groove with the stringer bead technique. The assumed steel density of the wire electrode was 7.85 g/cm. Every parameter set was repeated twice and the set wire feed rates monitored to assure the quality of the results. Current and voltage data sets were analyzed for a stable process condition without ramp up and ramp down. Depending on the welding speed, the analyzed data set contained 20 to 30 s of process data. The process power P_W and the overall power P_S were calculated according to Eqs. 1 and 2. EDE and the wall-plug efficiency were calculated according to Eqs. 4 and 3. Experiments for SGMAW were executed with the spray arc and the pulsed arc transfer. The process conditions are listed in Table 1. The arc process parameters were initially set by the synergic characteristic of the welding power source and adopted in case of a too high arc length or occurrence of spatters. The welding speed was increased with the wire feed rate in order to maintain a balanced material deposition in the groove. The process conditions of the TGMAW experiments are listed in Table 2.

Process parameters with alternating pulses were set by the synergic parameters for a SGMAW process and adapted to prevent spatter and fume formation. Process parameters for the asynchronous pulses were developed individually according to the needs of the process for a stable condition. Experiments with the ED transfer were conducted with synergic process parameters without modification (including the optimal contact tube to workpiece distance of 17 mm). Due to the limited frequency of the drive for the reversed wire motion, the maximum wire feed speed for TGMAW with ED transfer was limited to 17 m/min. Wall-plug efficiencies of the power sources were evaluated for the SGMAW process with a wire feed rate of 12 m/min and for the TGMAW process with alternating pulses with a total wire feed rate of 30 m/min.

2.3 Life cycle assessment for complete butt joints

According to the ISO standard, the methodology is divided into four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation in an iterative process [17]. First of all, the goal of this comparative LCA study is to evaluate the environmental effects of GMAW processes incorporating different energy efficiencies. Furthermore, the environmental impacts contributed by different inputs and outputs of the selected SGMAW and TGMAW processes are highlighted. The results are expected to provide information for welding process development and selection. The scope, namely the system boundary, of the study aims at the welding processes themselves, including the life cycle stages as material acquisition (considering raw material extraction and manufacturing of steel rods), manufacturing phase (carrying out welding processes), and waste management. In line with the system boundary, the consumption of electricity, materials and gases, and the landfill of waste are also covered. However, production and end-of-life management of welding machinery are not considered. The functional unit is 1 m weld seam of a 30-mm-thick metal plate. In this study, the CML 2002 method is adopted as the life cycle impact assessment method. The method is proposed by the Centre for Environmental Studies (CML) of the University of Leiden and focuses on a series of environmental impact categories expressed in terms of emissions to the environment [19, 26, 44]. GaBi 7.0 (by thinkstep) is used as the software to build and carry out the LCA model. In the life cycle inventory analysis phase, the inventory data of inputs and outputs of the chosen welding processes is collected according to the system boundary and the functional unit. Figure 2 shows the considered process input and output filler material, shielding gas, electrical energy, and direct emissions. Considered direct emissions were iron oxide fumes, nitrogen oxides, ozone, and carbon monoxide, which were assumed to be directly released in the environment.

Table 1 Process conditions for the SGMAW evaluation

SGMAW process	
Wire feed rates in m/min	10, 12, 14
Welding speed in mm/s	6–8
Type of shielding gas	82 % Ar, 18 % CO_2
Contact tube to workpiece distance in mm	18

Table 2 Process conditions for the TGMAW evaluation

	TGMAW alternating pulses	TGMAW asynchronous pulses	TGMAW ED transfer
Total wfr in m/min (lead wire/trail wire)	20 (10/10)	20 (10/10)	14 (9/5)
	26 (13/13)	28.5 (16/12.5)	16 (8.5/7.5)
	30 (16/14)	35 (20/15)	17 (9.5/7.5)
Welding speed in mm/s	10–14	10–14	10–16
Shielding gas	92 % Ar, 8 % CO_2	92 % Ar, 8 % CO_2	82 % Ar, 18 % CO_2
Contact tube to workpiece distance in mm	20	20	17

Considering the robustness, practicality, and the close relation between GMAW and steel-related industry, the four categories, global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and photochemical ozone creation potential (POCP), are selected for further comparison in the life cycle impact assessment stage [43]. In order to estimate the effects of the choices made regarding methods and data on the outcome of a study in the interpretation stage, a sensitivity analysis is conducted. Generally, uncertainties can result from differences in the conditions and assumptions. In the present case, a crucial assumption is the chosen electricity grid mix that is applied by the GaBi 7.0 software. The sensitivity analysis considers two scenarios. In the base scenario, the German electricity grid mix is adopted which is identical with the original LCA model. In the alternative scenario, the electricity data is changed to the European electricity grid mix. In the final phase of the LCA study, the results from life cycle impact assessments and the sensitivity analysis are interpreted.

Welding was carried out with the same equipment, steel grade, and seam preparation as for the energy efficiency investigations (see Section 2.2). The plates had a length of 600 mm and a width of 440 mm. The measured data for the weld seam length of 600 mm was scaled to the functional unit of 1 m. The SGMAW weld was executed with a spray arc material transfer and the TGMAW weld with asynchronous pulses. For SGMAW, a stringer bead technique was applied, and for TGMAW, a weaving bead technique was applied. Root passes of both variants were welded with SGMAW. Experimental conditions are shown in Table 3.

The filler wire consumptions were determined by the wire feed rate and welding time and were both set to the minimal needed amount. Electricity demand was determined by the data acquisition system described in Section 2.1. The total energy consumption values were adjusted according to an equal mass of deposited filler material in order to exclude the effect of uneven weld reinforcements. This was considered by reducing the energy consumption of the weld with the higher weld reinforcement according to the mass deviation between the two welds. The surplus energy was subtracted using the corresponding EDE value and the mass deviation. A standard rotameter was applied to control shielding gas flow rate. Electric energy for the robot movement was measured at the wall-plug of the robot and was determined using Eq. 1. The electricity consumption for the weld trajectory was added to the electricity consumption of the welding source to receive the overall electricity consumption. The total quantities of direct emissions were calculated according to emission rates of representative processes from literature [2, 22, 28, 31–33]. In case there was no appropriate data reported, fume emissions were scaled with respect to the deposition rate. Emissions of nitrogen oxides, ozone, and carbon monoxide were doubled for TGMAW.

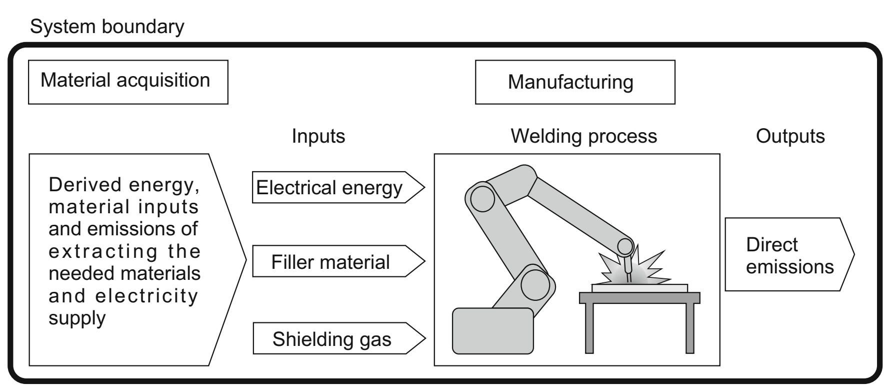

Fig. 2 The system boundary and considered inputs and outputs

Table 3 Process conditions for the comparative LCA of SGMAW and TGMAW

	SGMAW	TGMAW
Materials	S355 J2+N (DIN EN 10025-2)	
	Filler G 4Si1 (DIN EN ISO 14341)	
Groove preparation	V with 50° groove angle (ISO 9692-1)	
Total wfr in m/min	Root pass, 10	Root pass, 12.5
	Filler passes, 12.5	Filler passes, 20–35
Average welding speed in mm/s	6.7	6.4
Shielding gas	82 % Ar, 18 % CO_2	92 % Ar, 8 % CO_2

3 Results and discussion

3.1 Energy efficiency investigations

Figure 3 contains the energy efficiency of the SGMAW process. The shown EDE values are calculated from the arithmetic means of the repeated experiments. Error bars indicate the standard deviation of the measurements. The achieved EDE is between 560 and 620 g/kWh. For all wire feed speeds, higher energy efficiency of the pulsed arc transfer can be observed. Depending on the wire feed speed, the increase in energy efficiency ranges from 2.5 % at 10 m/min up to 6 % at 12 m/min. For a wire feed speed of 10 m/min, the differences of the EDE values between the pulsed and spray arc transfer are small and the ranges of the standard deviations are overlapping.

Figure 4 shows the results for the TGMAW experiments. All TGMAW processes show higher EDE values than SGMAW. TGMAW with the alternating pulses achieves the lowest energy efficiency values between 660 and 670 g/kWh. Additionally, the wire feed rate could not be increased over 30 m/min because of extensive fume formation and spatter. The highest deposition rates can be realized with asynchronous pulses, which yield energy efficiency values in terms of EDE between 714 and 781 g/kWh. The ED transfer gains the highest energy efficiency with 848 g/kWh at a wire feed speed of 17 m/min. However, the ED transfer offers the lowest deposition rates.

Figure 5 displays the measured wall-plug efficiencies of the process variants, which are all on a constant level. Wall-plug efficiencies of the SGMAW processes are between 84 and 85 %. A similar value was measured for the TGMAW variant with 85 %. Standard deviations of all measurements are below 1 %. A significant dependency of the wall-plug efficiency on the material transfer mode (spray or pulsed arc) or the process power PW cannot be observed.

The results for SGMAW are mainly consistent with expectations based on the findings for the effective efficiency (see Section 1) and confirm its implication regarding the energy efficiency. Due to less heat losses to the surrounding (observed, e.g., in [13]) and thus a higher effective efficiency, the pulsed arc transfer achieves higher EDE values than the spray arc. At a wire feed speed of 10 m/min, the difference between the spray and pulsed arc transfer with respect to the effective efficiency is small due to the

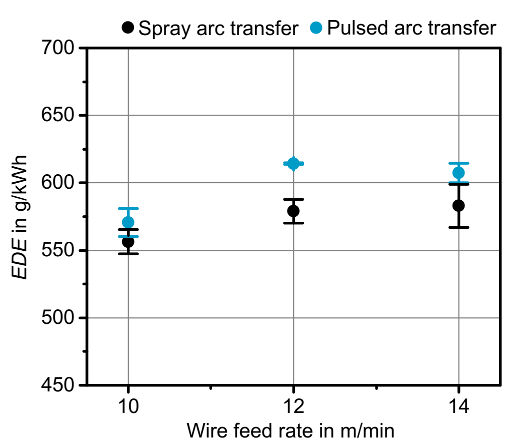

Fig. 3 Energy efficiency of SGMAW

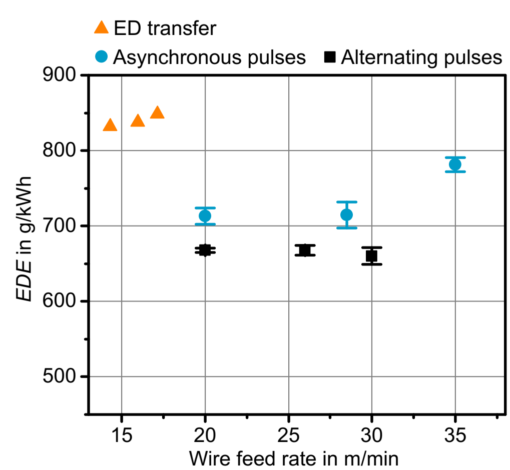

Fig. 4 Energy efficiency of TGMAW

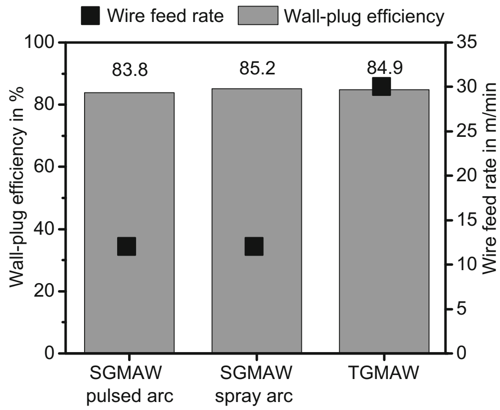

Fig. 5 Wall-plug efficiency of the equipment of different SGMAW and TGMAW processes

lower power level. However, the results imply that there is no clear relation to state that energy efficiency decreases while deposition rates and process powers increase. Thus, the effective efficiency does not provide justification for all of the results and the heat losses have to be compensated by other effects. TGMAW with alternating and asynchronous pulses yield higher energy efficiency than SGMAW despite the high process powers. An explanation of this issue can be provided by the higher electrode melting efficiency with higher process powers that was presented by Chandel [5]. Following the stated results in [5], the amount of energy used for melting the wire is increased while the higher process power is assumed to bring about higher energy losses to the environment. Thus, energy fractions used for heating the base material and for dissipation into the workpiece would be decreased accordingly. In consequence, as found in the present paper, higher process powers increase the energy efficiency of GMAW despite the reduced effective efficiency. The high energy efficiency of TGMAW with the ED transfer is in line with earlier findings of Pépe [27] and Hälsig [12] for SGMAW processes, which state that the needed process powers for a set wire feed rate are lower in contrast to a pulsed arc transfer. This is because the energy to melt the wire is generated by resistive heating to a high extent which incorporates less heat losses. Unfortunately, the deposition rates are limited which might be not suitable for cost efficient high power welding.

The presented values for the EDE can be well integrated with the findings of Hübner et al. [15]. The value for a TGMAW process in their work is 594 g/kWh at a wire feed speed of 20 m/min and thus slightly lower than the present figures for TGMAW with alternating pulses, which yielded 660 g/kWh for the same deposition rate. Causes for this deviation can be the source characteristic or the slight adjustments of process parameters for a short arc length made in the present study. The results of 781 g/kWh for asynchronous pulses are significantly higher than the values found by Hübner et al. because the process parameters for asynchronous pulses can be controlled individually and optimized with respect to energy efficiency. Additionally, the wire feed speeds and consequently the process powers were lower in [15] which can be a further reason for the observed process behavior.

Wall-plug efficiencies of the welding power sources are on the same level as published by Hälsig [12]. Consequently, a higher energy efficiency of a process leads directly to less electricity consumption because there is no effect of the material transfer mode or the process power. Still, around 15 % of the electricity is not used for welding but secondary functions (e.g., cooling unit, wire feeder). Therefore, future studies shall also focus on the wall-plug efficiency of welding power sources.

In summary, it can be stated that the energy efficiency of GMAW can be significantly enhanced by a tandem process. Among the TGMAW variants, the ED transfer is the most efficient but limited to a low deposition rate. A promising compromise is TGMAW with asynchronous pulses that improve energy efficiency and deposition rate at the same time.

3.2 Life cycle assessment for complete butt joints

The comparative LCA shows the potentials for reducing the environmental impacts of GMAW by a higher energy efficiency of the process. Cross sections of the produced SGMAW and TGMAW joints are shown in Fig. 6 incorporating the seam preparations. The life cycle inventory data as well as process data is shown in Table 4 based on the functional unit defined in Section 2.3. Comparing the SGMAW and the TGMAW process, the electricity consumption and the welding time are reduced by 24 and 55 %. Shielding gas usage was cut down by 19 %. The share of the welding robot of the overall electricity consumption was 4 % for

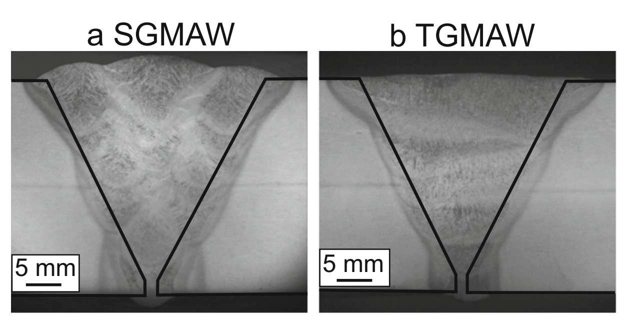

Fig. 6 Cross sections of the **a** SGMAW and **b** TGMAW welds

Table 4 Results of the process inventory

	SGMAW	TGMAW
Number of passes	16	6
Welding time in min	40	18
Average EDE (all passes) in g/kWh	568	735
Input/output for the LCA model		
Energy consumption in kWh	9.1	6.9
Filler material consumption in g	4200	4200
Shielding gas consumption in l	816	664
Direct emissions in g	FeO_x: 14	FeO_x: 22
	CO: 6.1	CO: 5
	NO_x: 0.12	NO_x: 0.1
	O_3: 0.4	O_3: 0.3

SGMAW and 2 % for TGMAW and thus of minor relevance. The measured average EDE values of both processes are in line with the results in Section 3.1.

The inventory is used to conduct life cycle impact assessments. By carrying out impact assessment within the CML 2002 method and GaBi 7.0 software, the environmental impacts in global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and photochemical ozone creation potential (POCP) contributed by the welding processes are estimated, as shown in Fig. 7. The results show that the application of the TGMAW process leads to significant impact reductions of the four selected categories. Depending on the impact category, the environmental burdens are reduced by 5 up to 11 %. The stated reduction of electricity consumption of 24 % does not lead to an environmental impact reduction of the same extent. Hence, the higher energy efficiency is not linearly transferred to the environmental burdens. Moreover, inputs and outputs show different influences on GWP, EP, AP, and POCP. In all chosen categories, the filler material dominates

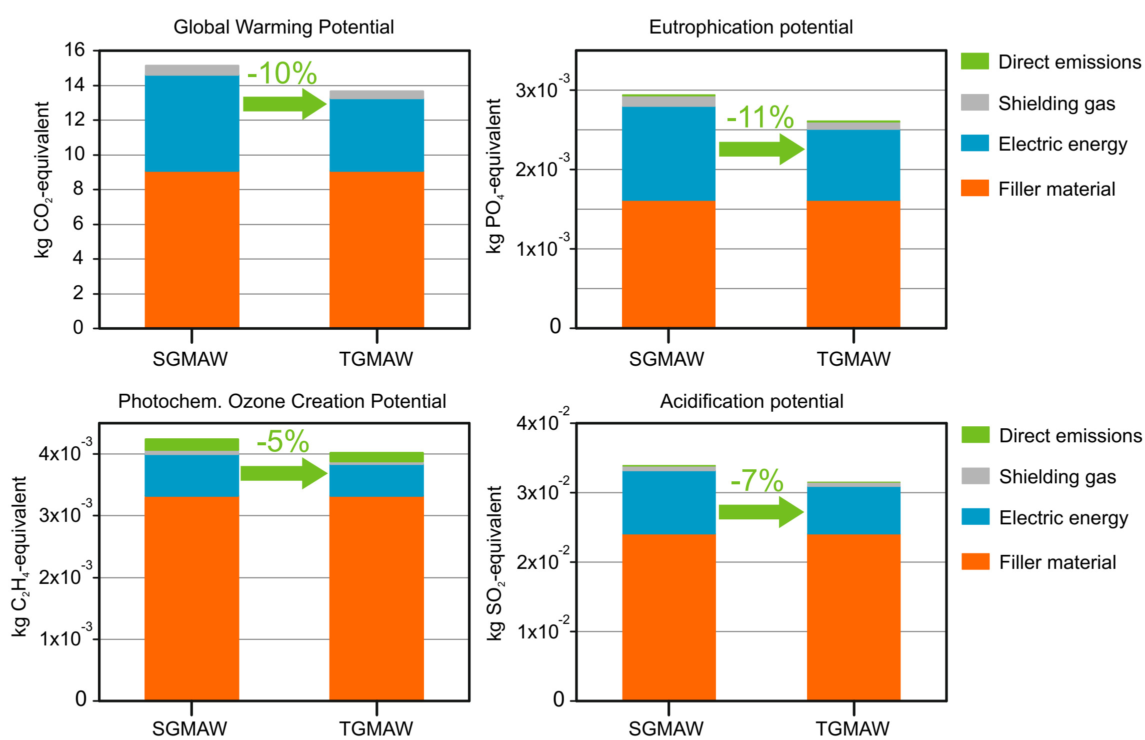

Fig. 7 Environmental profile of SGMAW and TGMAW

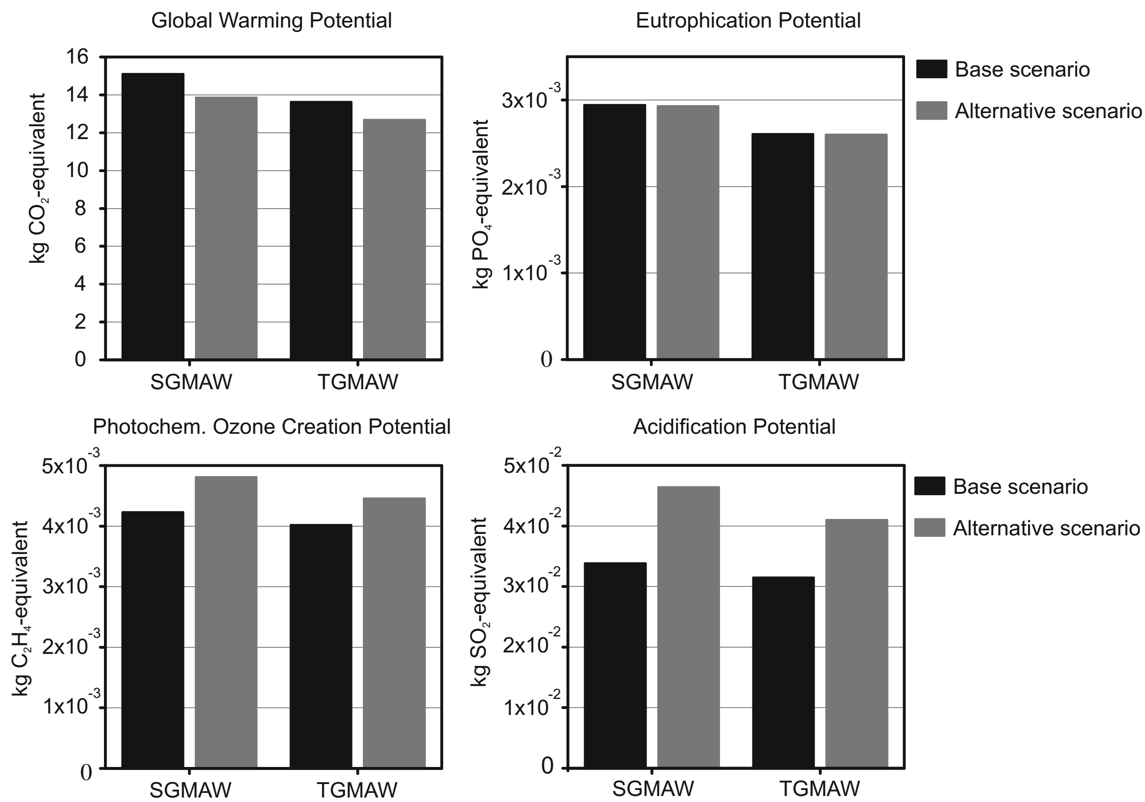

Fig. 8 Results of the sensitivity study

the environmental impacts. The contributions range from 54 % in EP to 78 % in POCP for SGMAW and from 61 % in EP to 82 % in POCP for TGMAW. The electricity consumption strongly influences GWP and EP with 36 and 40 % for SGMAW and 30 and 34 % for TGMAW. The shielding gas consumption and direct emissions from the process are of relatively minor significance for the presented environmental burdens. To sum up, higher energy efficiency of the TGMAW process led to the reduction of the electricity consumption of 24 % which reduced the environmental impacts up to 11 % in GWP, EP, POCP, and AP.

The sensitivity analysis enables the evaluation of the effects of different electricity grid mix data sets. Results of the two considered scenarios are displayed in Fig. 8. In the alternative scenario, the application of TGMAW still has an advantageous position in environmental performance in general. However, impact values change in all studied categories except EP. Consuming European electricity contributes more impacts than German electricity in AP and POCP, but slightly less in GWP. AP is remarkably affected by switching regional electricity grid mix data. The improvements in the categories GWP, POCP, and AP due to the higher energy efficiency of the TGMAW process change to 8, 7, and 11 %. Consequently, it can be generally stated that higher energy efficiency improves the environmental impacts of welding on a significant level. However, the detailed quantitative effects rely on the regional electricity production.

4 Conclusion

Energy-efficient manufacturing technologies are an essential instrument for fostering climate change and sustainable manufacturing. GMAW, one of the most frequently applied joining technologies, has been characterized with respect to energy consumption and efficiency. This enables industry to design energy-efficient welding procedures and allows detailed planning of the energy consumption of part manufacturing.

A data acquisition system has been set up to measure electricity consumption of the process and the equipment. As a gauge for measuring and controlling, the key performance indicator EDE was defined. EDE of SGMAW and TGMAW processes have been evaluated for various power levels and material transfer modes. Generally, all TGMAW variants reach higher values for EDE than SGMAW. In SGMAW, pulsed arc transfer is more energy efficient than the spray arc transfer. In TGMAW, the ED transfer is the most efficient variant followed by asynchronous pulses and alternating pulses, whereas asynchronous pulses reach the highest deposition rates among the tested variants. Wall-plug efficiency of the equipment was independent of the material transfer mode and the process power.

Furthermore, potentials for the reduction of environmental impacts of GMAW were demonstrated in a comparative LCA for butt joints of 30-mm-thick steel plates. TGMAW with asynchronous pulses has less environmental impacts than SGMAW with spray arc on the categories global warming potential, acidification, eutrophication, and photochemical ozone creation potential. The higher energy efficiency of the TGMAW process led to electricity savings of 24 % and a reduction of the environmental impacts of up to 11 %. Filler material and electricity consumption dominate the environmental burdens. The sensitivity study shows that the quantitative environmental benefits change with the type of sourcing of electricity.

Based on the presented results, it can be stated that economically efficient high power processes can also support environmental impact reductions. Further research towards increased energy efficiency of GMAW require intensive studies concerning the influence of changing welding power source characteristics and process parameters on the EDE.

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