NEW FINDINGS ON THE EFFICIENCY OF GAS SHIELDED ARC WELDING

A. Haelsig, M. Kusch and P. Mayr

ABSTRACT

A study was carried out to measure the effective efficiency of different gas shielded arc welding processes and investigate the role of influence coefficients on the process efficiency. A new system to measure the integrated heat flow in welding processes was developed and further investigated. By this system, it can be shown how e.g. electrical and welding torch parameters, as well as material and gas parameters directly influence the efficiency of the welding process. Through this, it is possible to raise the efficiency of welding processes for example by reducing the wire speed, using helium gas or increasing the distance of the welding torch to the metal plate. Contrary, increasing the current, welding speed or voltage reduces the process efficiency. The difference between the lowest and highest achievable value of efficiency can be more than 15 % for one specific welding process. In addition to the conventional welding processes like gas tungsten arc welding (GTAW), gas metal arc welding (GMAW) and plasma welding also latest technologies, such as heat reduced processes (for example controlled dip arc with or without wire pullback) and high performance welding processes were analysed. In this manuscript, primarily the new technology for measuring the efficiency is presented. Furthermore, different influence coefficients and their effects on the overall efficiency of welding processes are described. Finally, the differences between measured efficiencies and fixed values of efficiencies for welding processes given in standards are discussed. The efficiencies of the latest heat reduced and high performance welding processes are given. The results verify that the parametrical influence on the efficiency of welding processes is huge, so that it is not recommended to work with fixed efficiency values for example in modeling and simulation.

IIW-Thesaurus keywords: Effective efficiency; Arc welding; Calorimeter; Gas shielded arc welding.

1 Introduction

The generated heat Q of the welding process has a decisive influence on the properties of welded joints. It is the product of the electric work and the thermal efficiency η_{th} of the welding process in Equation (1) with electrical welding power P_S and welding time t_S [1, 2].

$$Q = P_s * t_s * \eta_{th} \tag{1}$$

This calculation is generally used to determine the energy input by unit length and the characteristic cooling time between 800 °C and 500 °C, $t_{8/5}$. This information can be translated to the conditions inside the welded zone and the heat-affected zone or can be used as input parameter for welding simulations.

Nowadays, determination of welding power P_S is exact due to direct measurement of voltage and current but still fixed values for the efficiency of welding processes are used. According to different welding standards, these values are not consistent [1, 2] and do not include the influence of parameters adjustable during welding, such as wire speed, gas flow, etc… [3].

For example, the European standard EN 1011-1:2009 lists following constant values for the efficiency of:

GTAW $\eta = 0.60$

Plasma welding $\eta = 0.60$

GMAW welding $\eta = 0.80$

In the standards, the values of thermal efficiency η_{th} include heat losses due to spatter, spillings, metal vaporization or heat losses of the welding arc [3]. By using measured values for the transferred heat into the welded part in relation to the measured welding power, the result is more precise and the term effective efficiency η_{eff} can be introduced.

Equation (2) with Q_{BM} as heat input into the base material and Q_{FM} as heat input by the molten filler material in relation to the welding power and time describes this effective efficiency:

$$\eta_{eff} = \frac{Q_{BM} + Q_{FM}}{P_s * t_s} \tag{2}$$

Working with fixed values of efficiency is critical, especially if using temperature sensitive materials. Effective efficiencies of energy reduced gas metal arc welding processes (for example event controlled dip arc processes with and without wire pullback) or high performance welding processes such as tandem GMAW and flat-wire GMAW are completely unknown.

Doc. IIW-2307, recommended for publication by Commission XII "Arc Welding Processes and Production Systems."

Within this work, effective efficiencies of different welding processes and their influence coefficients have been determined. To obtain these values, calorimetric measurements for the joining process have been performed for numerous configurations.

The aim of this paper is to present an overview of the new calorimetric measurement technique and show a review for different welding processes with varied welding conditions.

2 Calorimetric measurement system

The measurement of the efficiency of welding processes is realized with a new calorimetric measurement system, developed and further improved at Chemnitz University of Technology.

To analyse different gas shielded arc welding processes with one system, the classical equipment [4-7] has been modified.

For this purpose, an inclined metal plate is positioned at a certain angle in a thermally isolated calorimetric vessel (Figure 1). This positioning guarantees that the deformation, i.e. buckling in particular of thin plates has no influence on the measurement. The size of the metal plate is 1000 x 100 mm and can be of variable thickness from 1 mm up to 15 mm.

The heat input system, i.e. welding equipment, is moved with constant velocity and distance on top of the plate. This is realized by a robot handling system and guarantees the reproducibility of the experiment. Parallel to the movement of the welding torch, the water level in the calorimetric vessel is constantly increased. This allows that the distance between the plate at the location of the heat input system and the water level is low. This guarantees that the introduced heat, respectively energy, is directly transferred into the calorimetric medium and no insulating air film exists. To obtain a homogeneous temperature distribution in the vessel, the water is continuously circulated by pumping.

Inside the calorimetric vessel, highly sensitive thermocouples are positioned. This allows a measurement of the temperature difference of the water between start and end of the welding. At the beginning of the measurement, the water is at room temperature. This reduces heat losses of the water due to emission to the surrounding atmosphere so that they can be neglected in the analysis. After weighing the water volume, the integrated heat can be calculated as follows:

$$Q_{BM} + Q_{FM} = m_{water} {}^{*} c_{water} {}^{*} \Delta T_{calorimeter} \qquad (3)$$

With:

$Q_{BM} + Q_{FM}$ heat input by welding system [J]

m_{water} mass of water inside the vessel [± 10 g]

c_{water} specific heat capacity of water [kJ/(kg*K)]

$\Delta T_{calorimeter}$ temperature difference between process start and end [± 0.1 K]

3 GTAW process

The GTAW process is a universal and relatively easy controllable welding process, because no filler material is necessary. Therefore, these investigations started with this welding technique by just melting the plate material which is comparable to an autogenous gas weld.

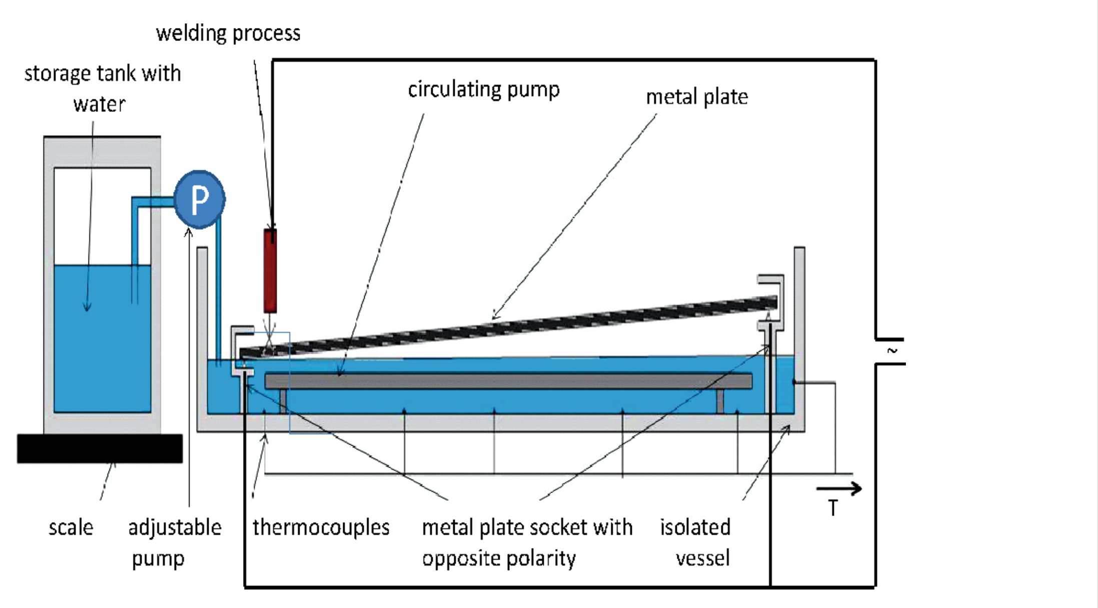


Figure 1 – Schematic of the setup for calorimetric measurements during welding

For this purpose, a water cooled GTAW torch was used. The average effective efficiency of the GTAW process for the reference welding parameters shown in Table 1 were calculated as $\eta_{eff} = 0.76$.

By varying the welding parameters, a minimum value of effective efficiency (GTAW) of $\eta_{eff} = 0.68$ and a maximum value of $\eta_{eff} = 0.79$ can be achieved. This shows that just by variation of welding parameters the range of effective efficiency for GTAW can vary by 11 %.

As a first step, the welding power has been varied by changing welding current, distance between electrode and plate and the shielding gas. Varied parameters, range of variation and the change in efficiencies are listed in Table 2.

To investigate factors influencing the efficiency of GTAW welding, different defined welding factors were varied based on the shown reference parameters (Table 1).

Increasing welding current in steps of 50 A results in a continuous reduction of the effective efficiency. The main reason is the increasing emission losses of the growing welding arc and the increasing temperature gradient between welding arc and surrounding atmosphere.

Raising welding voltage by increasing the distance between electrode and plate in steps of 1 mm has a similar effect. The resulting surface area of the welding arc increases as a function of the increasing distance between electrode and plate so that the emission losses to the atmosphere increase as well.

Substituting argon in steps of 25 vol. % by helium raises the welding power without significantly influencing the effective efficiency of the GTAW process (see Table 2).

Investigations on the influence of the polarity reveal that for alternating current, raising the fraction of positive polarity of the electrode reduces the effective efficiency. Increasing the fraction of positive polarity of the electrode reduces the heat input into the plate. The effective efficiency of GTAW using alternating current (50 % positive polarity) is about 10 % lower compared to direct current with a negative poled electrode.

Adding filler material to the GTAW process reduces the effective efficiency by an average of 6 %. Melting filler material requires energy and an additional amount of enthalpy of fusion. Additionally, there are also higher efficiency losses due to an increased amount of metal vapour.

4 Plasma arc welding

For plasma arc welding, a water cooled welding torch was used. The average effective efficiency for the plasma arc welding process for the reference parameters shown in Table 3 is $\eta_{eff} = 0.75$.

The focused and compressed plasma welding arc allows a much higher heat transfer than the GTAW process. The emission losses to the surrounding atmosphere are reduced. On the other hand, much energy is lost through the cooling of the plasma gas nozzle. These two effects compensate each other and this is why plasma arc welding and GTAW do nearly have the same effective efficiencies. Also the influence coefficients show the same tendencies.

Table 1 – GTAW parameter sets that resulted in minimum, reference and maximum effective efficiencies

parameter	min. eff.	reference efficiency	max. eff.
electrode diameter	3.2 mm	3.2 mm	3.2 mm
point angle electrode	20 °	20 °	20 °
distance electrode/plate	4.0 mm	4.0 mm	3.0 mm
polarity of electrode	50 % plus, AC	minus, DC	minus, DC
welding current	150 A	150 A	50 A
shielding gas	Argon	Argon	Argon
shielding gas flow	15 l/min	15 l/min	15 l/min
effective efficiency	**0.68**	**0.76**	**0.79**

Parameters: bead on plate, heat conduction mode

Table 2 – Level of influence of current, distance and shielding gas on welding power and effective efficiency for GTAW

varied parameter	range of change	ΔP_S	$\Delta\eta_{eff}$
welding current	50 to 300 A	+690 %	-7.8 %
distance	2 to 8 mm	+41 %	-8.3 %
shielded gas	Ar to He	+47 %	+3.0 %

Reference parameters as shown in Table 1

Table 3 – Plasma welding parameter sets that resulted in minimum, reference and maximum effective efficiencies

parameter	min. eff.	reference efficiency	max. eff.
electrode diameter	4.0 mm	4.0 mm	4.0 mm
point angle electrode	20 °	20 °	20 °
diameter of plasma gas nozzle	2.5 mm	2.5 mm	2.5 mm
distance electrode/plate	6.5 mm	6.5 mm	4.5 mm
polarity of electrode, DC	minus	minus	minus
welding current	100 A	100 A	50 A
shielding/ plasma gas	Argon	Argon	Argon
plasma gas flow	2 l/min	4 l/min	4 l/min
shielding gas flow	10 l/min	10 l/min	10 l/min
effective efficiency	**0.69**	**0.75**	**0.80**

Parameters: bead on plate, heat conduction mode

By varying the welding parameters, a minimum value of effective efficiency of $\eta_{eff} = 0.69$ and a maximum value of $\eta_{eff} = 0.80$ can be observed. This shows that just by variation of welding parameters the range of effective efficiency for plasma welding can vary by 11 %.

5 Gas metal arc welding (GMAW)

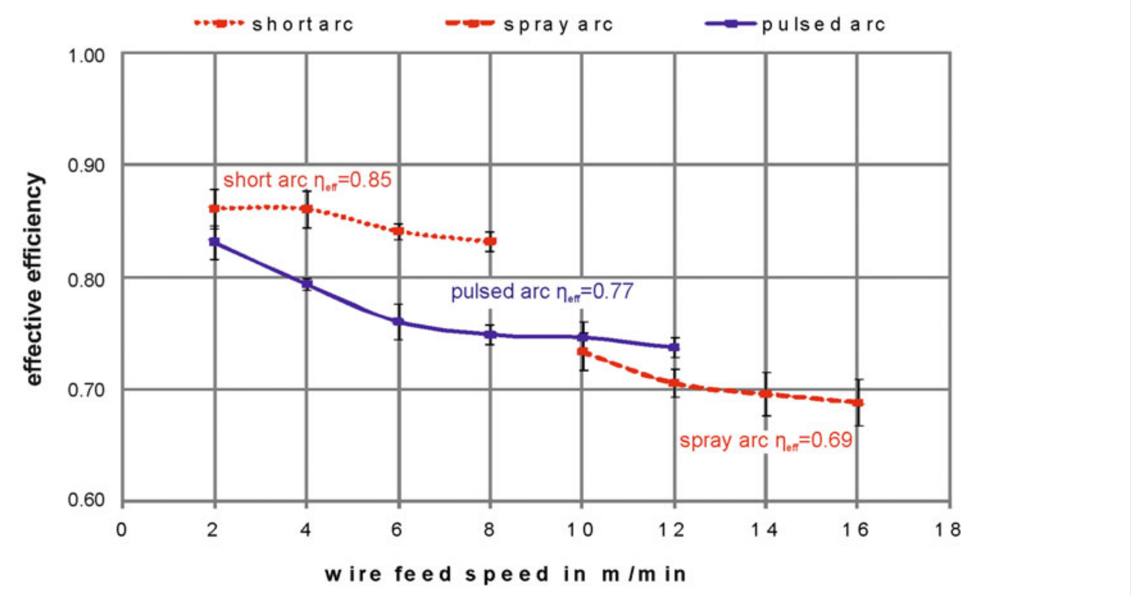
For GMAW, a water-cooled welding torch and representative power source characteristics were used.

Changing welding power requires an adaption of the wire feed speed and as a result the welding arc changes from short arc to spray arc. During short circuiting dip transfer phase, transport of the electric energy takes place by resistance heating of filler material and a direct energy flow between filler and base material is observed. During the time between two successive short circuits the arc burns. Here, the arc length is short hence the heat losses to the surrounding atmosphere are low. This is why the effective efficiency of the dip transfer is high and that of the short circuit is low. By changing the welding arc to spray arc (higher wire feed speed) the energy transfer changes and takes place without short circuiting so that the effective efficiency is lower.

Characteristically, the pulsed arc changes between high and low current phases in order to avoid short circuit or to reduce the heat input at higher power levels. The effective efficiency of the pulsed welding arc is between that of the dip transfer and spray arc. The influence of the welding arc on the effective efficiency is shown in Figure 2.

There are two ways of energy transfer from the welding torch into the plate. One way is the resistance heat of the filler material and the molten filler material and the other way is heat transferred through the welding arc.

To allow a comparison of the two ways of heat transfer, a spray arc with reference parameters given in Table 4 was varied. The results are summarised in Table 5.



parameters: as shown in Table 4 for steel filler material

Figure 2 – Influence of the welding arc on the effective efficiency of GMAW

Table 4 – Reference parameters for GMAW of steel and aluminum (bead on plate weld)

parameter	steel	aluminum
wire feed speed	10 m/min	
electrode material	G3Si1	S Al 5183
electrode diameter	1.2 mm	
distance contact tube/plate	18 mm	
shielding gas	M12	I1
shielding gas flow	15 l/min	
welding voltage	30.8 V	24.0 V

Table 5 – Magnitude of influence for GMAW of steel and aluminum (parameters: as shown in Table 4)

parameter	range	DPS	Dheff
steel			
welding voltage	28 to 32 V	+33 %	−10,9 %
distance	15 to 30 mm	−26 %	+8,2 %
aluminum			
shielding gas	Ar to He	+27 %	+8,7 %
filler material			
steel to aluminum material		−62 %	+7,1 %

Raising the welding voltage in steps of 0.5 V, a continuous decrease of the effective efficiency is observed. An explanation for this is the increasing emission losses of the growing welding arc and the increasing temperature gradient between welding arc and surrounding atmosphere.

Changing the energy transfer to resistance heating of the filler material by increasing the stick out length in steps of 3 mm, the effective efficiency does raise. A larger fraction of energy is used to heat the filler material (as per Joule´s law) and less energy is lost through the spray arc as the temperature gradient to the surrounding atmosphere is reduced.

The melting temperature of aluminum is lower compared to that of steel so less power is necessary for melting. Measurements show that the emission losses are more than three times lower when using aluminum filler material. This is approximately to the same extent, as the welding power is lower in order to realize the same wire feed speed. It can be concluded that metal inert gas (MIG) welding of aluminum is more efficient than metal active gas (MAG) welding of steel when realizing the same wire feed speed.

Looking at shielding gases, helium has a positive influence on the effective efficiency.

An increasing level of CO_2 in the argon shielding gas (5-15 % CO_2) shows no interpretable influence on the effective efficiency.

In summary, a classification in terms of effective efficiency of GMAW processes by welding arc is a result of this investigation, as it is shown in Table 6. This proves once more that classical fixed values for efficiencies are not meaningful and provide false results.

6 High performance welding

For typical high performance welding processes, tandem GMAW and flat wire GMAW-welding are investigated.

As a matter of principle, the coefficients of influence of both processes are the same as compared to that of the standard GMAW process. The effective efficiency is reduced by raising the wire feed speed or raising the welding voltage.

Also the shielding gas type, the filler material and the distance between contact tube and plate have a strong influence on the effective efficiency.

The advantage of these high performance processes is the high deposition rate, as it is shown in Figure 3. By definition, high performance processes start at melting deposition rates of 8.5 kg/h. This is the point where the standard GMAW-process has the lowest effective efficiency.

High performance welding processes do have a different type of welding arc and heat transfer. This is why the differences in effective efficiencies are generated.

7 Modified energy-reduced GMAW processes

Pulsed processes (MIG-pulsed and MIG-AC) and event controlled dip arc processes with and without wire pullback were compared to each other. Applications in the

Table 6 – Classification of GMAW for steel and aluminum by the type of welding arc in terms of effective efficiency

welding arc	effective efficiency
steel	
dip transfer	0.85
pulsed arc	0.77
spray arc	0.69
aluminum	
dip transfer	0.87
pulsed arc	0.84
spray arc	0.76

Parameters: wire feed speed 2 to 16 m/min; distance contact tube/plate 18 mm; welding speed adapted to wire feed speed from 40 to 110 cm/min; shielding gas flow 15 l/min range of lower welding power level for MIG-brazing and MIG-aluminum welding were also investigated, as it is shown in Table 7.

In each case, the effective efficiency decreases by increasing the wire feed speed. The efficiency is a function of the process design and current-voltage characteristic of the welding power source. Due to the complex welding process characteristics, at this stage, some observed variations in the effective efficiencies are not fully understood and are still investigated.

8 Conclusions

Process dependent effects on the effective efficiency of gas shielded welding processes were investigated by a new calorimetric measurement system and illustrated. Through this new experimental design, the realistic heat input into the base material can be measured. Results of these investigations can be used for determining optimum welding parameters for welding of temperature sensitive materials, such as fine-grained steels or as basis for process and material simulation models.

By this experimental setup, measurements of exact values of effective efficiencies for different welding processes, as well as comparison of different influence coefficients and types are possible.

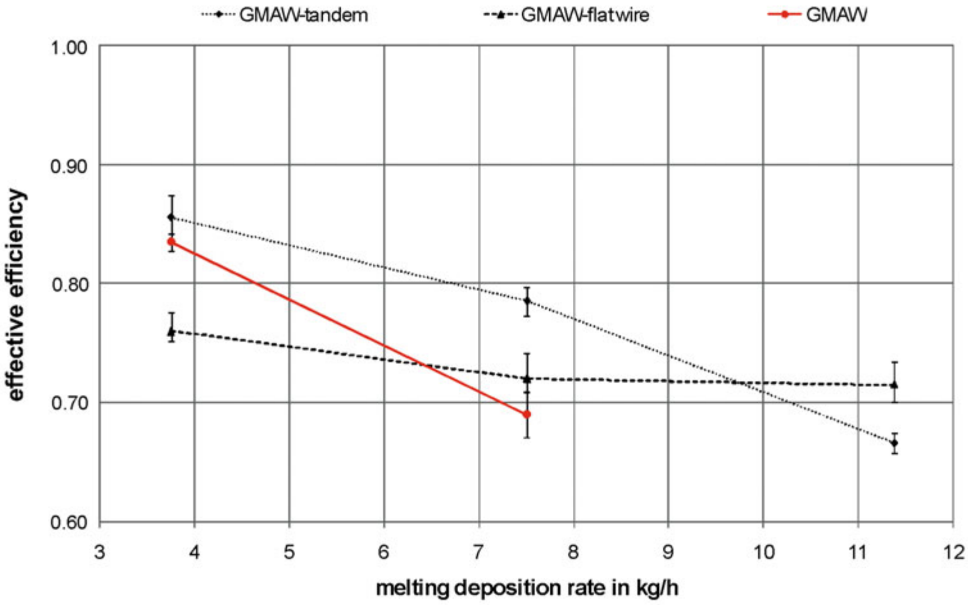
GTAW and plasma welding have a mean effective efficiency, over a wide range of process parameter, of 0.75. Increasing welding current or distance between electrode and plate decreases the efficiency. Increasing the shielding gas flow raises the effective efficiency.

A classification of GMAW-processes by welding arc was possible, as it is summarized in table 6. Classical fixed values for effective efficiencies, as given in several standards, are not meaningful and provide false results.

Table 7 – Effective efficiencies of different energy reduced GMAW processes

process	filler material d = 1.0 mm	
	S CU 6560	**S Al 5183**
	(CuSi3Mn1)	**(AlMg4,5Mn0,7)**
MIG-pulsed	0.79	0.83
MIG-AC	0.74	0.81
controlled dip arc with wire pullback	0.84	0.84
controlled dip arc without wire pullback	0.72	0.82

Parameters: wire feed speed 2 to 8 m/min; distance contact tube/plate 18 mm; welding speed adapted to wire feed speed from 30 to 60 cm/min.



Parameters: wire feed speed 2 to 18 m/min; distance contact tube/plate 18 mm; welding speed adapted to wire feed speed from 60 to 120 cm/min; shielding gas flow 20 l/min; filler material GMAW flat wire Tapex SG3 0,6 x4 mm, GMAW tandem steel electrode diameter 1,2 mm

Figure 3 – Influence of the melting deposition rate on the effective efficiency of high performance welding processes compared to standard GMAW

With the constraint of producing a good quality welding seam, the welding parameters have been varied from the reference. In consequence, minimal and maximal values of effective efficiencies have been measured:

- **GTAW**

  Minimum: $\eta_{eff} = 0.68$

  Mean value: $\eta_{eff} = 0.76$

  Maximum: $\eta_{eff} = 0.79$

  (→ $\Delta\eta_{eff} = 11$ %)

- **Plasma welding**

  Minimum: $\eta_{eff} = 0.69$

  Mean value: $\eta_{eff} = 0.75$

  Maximum: $\eta_{eff} = 0.80$

  (→ $\Delta\eta_{eff} = 11$ %)

- **MAG welding** (steel electrode)

  Minimum: $\eta_{eff} = 0.68$

  Maximum: $\eta_{eff} = 0.86$

  (→ $\Delta\eta_{eff} = 18$ %)

- **MIG welding** (aluminum electrode)

  Minimum: $\eta_{eff} = 0.73$

  Maximum: $\eta_{eff} = 0.91$

  (→ $\Delta\eta_{eff} = 18$ %)

Using modified energy-reduced GMAW processes, the effective efficiency decreases by raising the wire feed speed. The efficiencies are approximately the same level as for the standard processes, but a reduced heat input into the base material has been measured.

High performance welding processes do have a better effective efficiency as the standard GMAW-process by using the high performance welding range.

At present these investigations are continued at Chemnitz University of Technology.

Acknowledgements

This work was part of research project IGF Nr. 15.562B/DVS-Nr. 03.0378 of the research coalition "Deutscher Verband für Schweißen und verwandte Verfahren e.V." (DVS) and was promoted by the program for industrial alliance research (IGF). The financial support by "German Federal Ministry of Research and Technology" via the consortium "AiF" is gratefully acknowledged.

The Cluster of Excellence "Energy-Efficient Product and Process Innovation in Production Engineering" (eniPROD®) is funded by the European Union (European Regional Development Fund) and the Free State of Saxony.

References

[1] DIN EN 1011-1: Welding – Recommendations for welding of metallic materials – Part 1: General guidance for arc welding; German version EN 1011-1:2009.

[2] SEW 088, supplemental sheet 2: Weldable fine grained steels; guidelines for processing, particular for fusion welding, 1993.

[3] Schellhase M.: Der Schweißlichtbogen- ein technologisches Werkzeug (The welding arc, a technological tool), Verlag Technik, Berlin 1985 (in German).

[4] Pepe N. and Yapp D.: Measurements of process efficiency for a range of MIG/MAG welding process, 17th International Conference Computer Technology in Welding and Manufacturing, Cranfield, GB, pp. 1-11, 2008.

[5] Shinoda T., Hayashi C. and Kato Y.: Directed plasma fabrication, Proceedings of the International Conference of Materials, Helsingor, DK, pp. 258-267, 2001.

[6] DuPont J. N.: Thermal efficiency of arc welding processes, Welding Journal, vol. 74, pp. 406-416, 1995.

[7] Giedt W. H. , Tallerico, L. N. and Fuerschbach P.W.: GTA welding efficiency: calorimetric and temperature field measurements, Welding Journal, vol. 68, pp. 28-32, 1989.

About the authors

A. Haelsig (andre.haelsig@mb.tu-chemnitz.de), M. Kusch (mario.kusch@mb.tu-chemnitz.de) and P. Mayer (peter.mayr@mb.tu-chemnitz.de) are with Chemnitz University of Technology, Chair of Welding (Germany).