TB, SS, UK, MST/319890, 2/12/2009

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **20** (2009) 000000 (7pp) UNCORRECTED PROOF

Improvement of the control of a gas metal arc welding process

Gregor Gött[1], **Heinz Schöpp**[1], **Frank Hofmann**[3] **and Gerd Heinz**[2]

[1] INP-Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany
[2] GFaI, Rudower Chaussee 30, 12489 Berlin, Germany
[3] TU-Berlin, Fakultät V Verkehrs- und Maschinensysteme, Institut für Werkzeugmaschinen und Fabrikbetrieb, Fachgebiet Füge- und Beschichtungstechnik, Pascalstraße 8-9, D 10587 Berlin, Germany

E-mail: schoepp@inp-greifswald.de

Received 28 May 2009, in final form 19 November 2009
Published DD MMM 2009
Online at stacks.iop.org/MST/20/000000

Abstract
Up to now, the use of the electrical characteristics for process control is state of the art in gas metal arc welding (GMAW). The aim of the work is the improvement of GMAW processes by using additional information from the arc. Therefore, the emitted light of the arc is analysed spectroscopically and compared with high-speed camera images. With this information, a conclusion about the plasma arc and the droplet formation is reasonable. With the correlation of the spectral and local information of the plasma, a specific control of the power supply can be applied. A corresponding spectral control unit (SCU) is introduced.

Keywords: gas metal arc welding, pulsed arc, argon, spectroscopy, spectral control unit, high-speed photography, photodiodes

(Some figures in this article are in colour only in the electronic version)

1. Introduction

*G*as *m*etal *a*rc *w*elding (GMAW) is a conventional process for semi-automatic or automatic joining processes. It works with a continuous consumable electrode and can be used for different materials and power ranges. Currently, joining of thinner sheet materials is of great interest in the metal working industry. This is due to the fact that energy and money can be saved by using thin sheets of zinc-coated steel or light aluminium alloys. Since GMAW was developed for a variety of materials, there is a great interest in improving this joining process furthermore for these thinner sheet materials especially in the automotive industry.

A common method of metal transfer for the GMAW of aluminium materials is the pulsed arc. It supports a wide range of parameter settings with stable conditions. Therefore, it is versatile for joining thinnest laminations.

Distinctive for this process is a pulsed current, which melts the filler wire and allows the formation of a small molten droplet with each pulse. By setting the right parameters, the process can be adapted for different material dimensions, and an optimal pulsed arc can be adjusted. This leads to a stable process suitable for many alloys. However, when welding aluminium, its low melting point can be a problem. If the energy input is slightly too high, the welding pool falls through the joint and ruins the work piece permanently, especially with thin sheets of approximately 1 mm thickness. Setting the right parameters was a problem of trial and error.

So far, the energy input during the melting phase of the filler wire takes place via a rigid cycle. In such rigid cycles, the base and the current pulse alternate in a predetermined way without considering the current status in each pulse. To find optimized cycles for different applications, various filler materials and shielding gases, complex trials are necessary. Current–voltage characteristics are derived and saved in the welding-machine controller. Differences between the normal use and the performed tests to derive the characteristics occur. Variations of the burner contact resistance, the current contact tube distance, the plasma composition and the environment (gas flows, temperature and humidity) might result in deviations of joint quality and induce sputters and isolated inclusions.

This set of problems has been under investigation in recent years [1]. The aim is to find additional information from the process, other than the electrical ones (current and voltage), to influence and control it. There is an increasing number of papers about the use of spectral analysis as a source of additional information about the process, most of them about *t*ungsten-*i*nert-*g*as (TIG) processes but also about laser processes [2–7].

This work deals with the use of spectral information of the arc plasma to provide a basis for an improved control of the energy input in the process. The aim is to accomplish an optimal energy input into the welding joint in respect of both a steady material transfer and avoidance of defects in the joining process.

Earlier investigations showed that a promising approach is a real-time processing of significant spectral information of the arc. Optical signals would not be influenced by the large electro-magnetic fields around the welding machine. Therefore, a correlation between light intensity and the status of the process has to be found. This correlation has to be used to predict conditions which lead to the release of a molten droplet.

A combination of high-speed photography with metal-interference-filter and a fast data collection with a spectrometer in a certain spectral range was accomplished to gain the necessary information. This was performed in two steps: a parallel acquisition of a spectral overview from 480 to 820 nm with the spectrometer and a signal intensity measurement with spectral selective diodes.

The analysis of lines selected from the spectral overview was necessary to find the metal vapour concentration. Therefore, knowledge of the spatial distribution of the plasma properties, e.g. temperature and plasma composition, is the premise to understand the time-dependent operation of the process.

An expensive *o*ptical *e*mission *s*pectroscopy (OES) set-up was used to find the desired spectral ranges for special selected photodiodes. With these diodes and a suitable comparison circuit, very short response times can be achieved. Each current pulse of the examined process lasts for around 2 to 3 ms, depending on the settings with a plateau and a down-slope phase of around 1 ms. In the end of this high-current phase, the droplet is supposed to be released due to the pinch force. The pulse also has to be as short as possible to keep a low energy input per unit length. Therefore, there is only a short-termed time period to detect the current situation inside the arc and adjust the welding machine controller. It was estimated that an optical control unit needs a response time of about 50 to 100 μs. The control unit has to adjust the energy input during the high current pulse individually for each pulse in contrast to the rigid cycles of common welding machine controllers.

Unlike laser beam or hybrid welding, this application offers a solution with lower operating costs for small- and medium-sized businesses. GMAW is less error prone in respect of component tolerance and material parameters than similar processes with higher costs. This advantage is increased by adjusting the energy input of the transfer pulse in real time. Therefore, the competitive position of GMAW has the potential to be improved considerably.

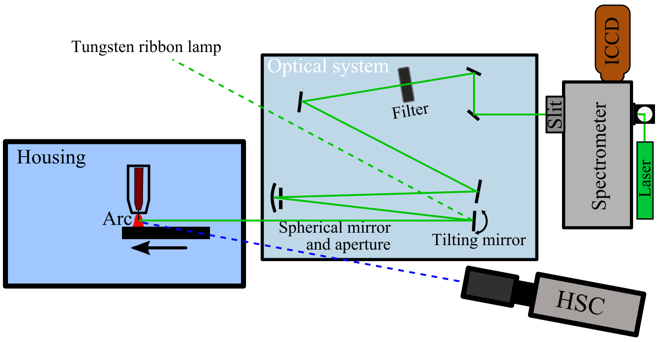


Figure 1. Set-up with a housed arc, the spectrometer and the high-speed camera. The optical paths are schematically drawn.

2. Experimental set-up and spectroscopic observation

The measuring set-up is shown in figure 1. It consists of a spectrometer with three different gratings, an optical system that contains one spherical mirror, several planar mirrors and a filter. An *i*ntensified *c*harge-*c*oupled *d*evice (ICCD) is a two-dimensional device, which records spatially resolved spectra of the light. The ICCD controller allows a pulsed acquisition controlled by a trigger, so a phase-resolved measurement is possible. By means of a tungsten ribbon lamp, the absolute calibration of the measured spectra was possible by imaging it alternatively onto the spectrometer slit via a tilting mirror. With the aid of pen rays (these are lamps with well known spectral lines) for argon and other appropriate elements the wavelength calibration has been carried out. The adjustment of the optical path before the measurements is done by a laser beam coming from the backside of the spectrometer to ensure the vertical position in the arc. So it is possible to vary the position above the work piece.

Images of the process were also recorded by a high-speed camera (HSC, REDLAKE HG-100K) with 20 000 frames s^{-1}. So, the geometrical information of the images could be compared with the spectra of the cross section of the plasma arc. Disturbances due to process instabilities can be better observed with the pictures than with the spectra. Spectrometer images with irregularities had been excluded from analysis.

The electrical data (current and voltage) of the welding process were measured by an oscilloscope (TEKTRONIX TDS 754A), a voltage probe (P5200) connected to the torch and a current transformer (LEM HAL 200-S). Synchronously, trigger pulses for the ICCD and high-speed camera are recorded.

In a first step, two processes of pulsed short arcs have been investigated. A pulsed arc brazing process (with a CuAlZn filler wire on zinc-coated steel) and a welding process (with AlMg4.5Mn0.7 alloy) were investigated. Figure 2 gives an overview of the spectral distribution of the two observed processes at positions in the middle between the wire and the basic material. The spectral resolution was about 0.34 nm/pixel with a 150 mm^{-1} grating. The measured lines could be associated with the existing elements in the arc. The result of this method was the predominance of the metal lines below 550 nm, whereas the argon lines were residing above

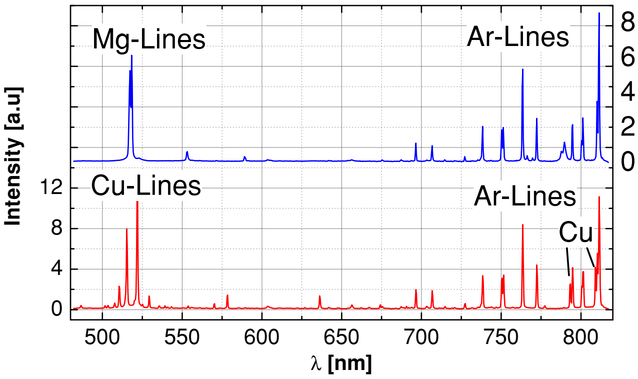


Figure 2. Comparison of overview spectra of the two observed processes with two characteristic line groups during current maximum.; upper: AlMg welding process; lower: CuAl brazing process.

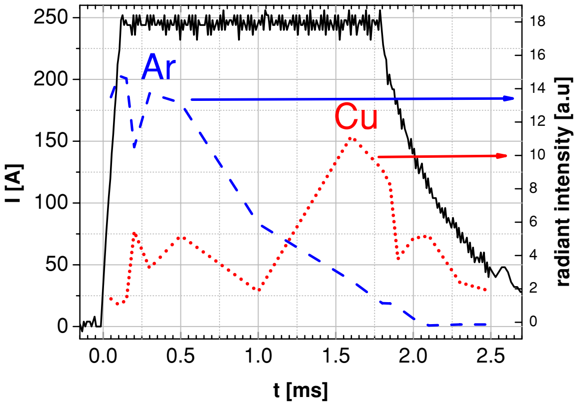
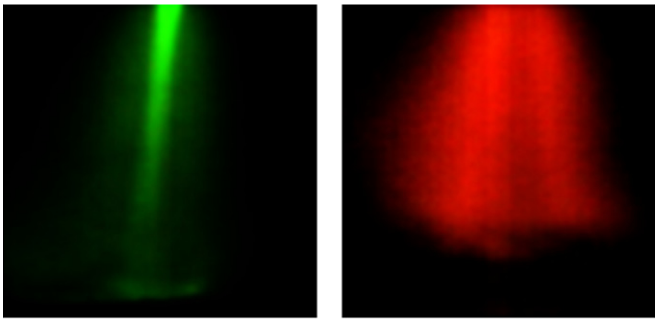


Figure 3. Current pulse (black line) and radiant intensities of Ar (794.8 nm) (blue dashed) and Cu (793.3 nm) (red dotted) for the CuAlZn filler wire.



(*a*) 575 nm-filter (*b*) 750 nm-filter

(*c*) without filter

Figure 4. High-speed camera pictures of the pulsed arc (∼1 ms after starting the current pulse) obtained with different metal interference filters (*a*), (*b*) and without filter (*c*) for the CuAlZn filler wire.

690 nm. This information is important for developing the control unit and will be discussed in detail later on.

For a first analysis of the welding processes, the measured radiant intensities have been investigated. The intensity distribution is integrated over the nominal wavelength and line wings for each line and further over the spatial distribution. So, one obtains the whole energy output of the line. The procedure is done for two discrete lines of the same element (e.g. Ar) in order to avoid disturbances by unwanted elements. Since those lines were close together (<2 nm), it is possible to compare them with each other in the same spectral range.

In a different case with lines of different elements, a high-resolution grating of the spectrometer was used. One line was emitted by Cu at 793.3 nm and another by Ar at 794.8 nm. Figure 3 shows the time behaviour of the intensity distribution (integrated value as explained above) of the two lines during the current pulse.

It became evident that there is a characteristic behaviour of each pulse. The intensity of the Ar lines decreases during each pulse and the Cu lines increases. If the appropriate relationship between these two intensities is reached, the current can be diminished. The change in current leads to the pinch effect by electromagnetic forces which support the droplet formation. The relationship between Ar and Cu intensities was chosen by trials in the past.

The spatial distribution and the temporal behaviour can also be observed using a high-speed camera with metal interference filters (these are band-pass filter that contains several thin layers which are manufactured in a way to cause destructive and constructive interference of predetermined wavelength; thereby one can achieve a narrowband filter). Periodic changes of emitting elements inside the arc can be distinguished in the images (figure 4). Due to the spectral distribution of the elements, interference filters for 575 nm and 750 nm were used to observe the Cu lines (figure 4(*a*)) and the Ar lines (figure 4(*b*)), respectively. Figure 4(*c*) shows the arc without any filter. Analysis of the three synchronous images reflects the periodic change of the element distribution inside the arc. The left picture (figure 4(*a*), 575 nm for Cu—green) shows a development of a tight core with radiating copper, whereas the right picture (figure 4(*b*), 750 nm for Ar—red) shows the bell-shaped plasma with a hollow centre. The darker zone is due to the lower density of the argon and its higher excitation energy; therefore, the copper dominates this zone by its radiation. The effect is only visible with aid of suitable filters.

The same behaviour for magnesium lines is observable with the aluminium welding process. The development of the intensity has also been compared with the high-speed camera. Periodically increase of the radiant intensity between 480 and 550 nm is reasoned by the raising temperature of the filling wire heated by the hot shielding gas during each pulse. The higher temperature triggers a higher evaporation of the metals.

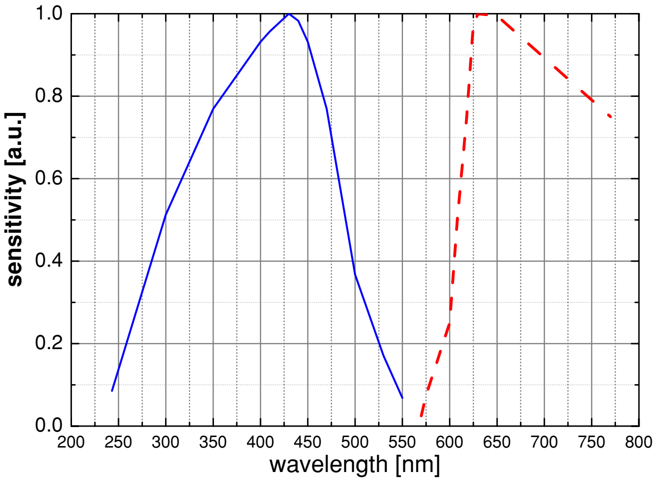


Figure 5. Spectral sensitivity characteristics of two selected photodiodes, both normalized to 1 (solid line: UV sensitive; dashed line: IR sensitive).

Certainly, the experimental setup of figure 1 is expensive and not useful for industrial approaches. However, looking for a reasonably priced solution with fast detectors that could be implemented and influence the machine control, different spectral-sensitive photo-diodes come into focus. Lots of experiments were done using several sensitive diodes simultaneously. Diodes are chosen to record separately the different parts of the spectrum. It should also be able to analyse diverse ranges of wavelength, for example on one hand from 480 to 550 nm and on the other hand from 690 to 830 nm, where metal lines or shielding gas lines are predominant, respectively. By performing a comparison between the observed spectra (figure 2) and sensitivity curves (figure 5), the optimum combinations of photodiodes can be obtained.

3. Signal processing and control unit

The SCU has to impact the energy input by the welding machine in real time. For every current pulse, the energy input should be sufficiently powerful to activate a droplet. This means that the temperature in the plasma should be high enough to create a droplet but should not be too high to avoid spillings. In the other case, if no droplet is activated, the SCU should start the machine for a new current pulse.

For that purpose, photodiodes had to be selected to record optical spectra with up to 192 kS s^{-1}. At the beginning, the signal strength was recorded with up to six independent optical channels from infrared (IR) to ultraviolet (UV). Two spectral selective photodiodes were considered to be the optimal combination to observe the investigated process. Figure 5 shows the relative sensitivity of those two diodes within the spectral range from 200 to 800 nm. The one labelled ‘UV’ is sensitive to ultraviolet to blue and the ‘IR’ to red and infrared. The signal strength was adjusted by a specific ‘zero-point-offset amplifier’.

A differential measurement approach was developed to account for distance and surface influences as well as reducing the influence of the target emissivity. In addition, the different sensitivity and active area of IR and UV diodes had to be considered in the development of the amplifier of the diodes. Here, the IR diode has a 30 times higher sensitivity and a 140 times larger active area in comparison with the UV diode. This leads to a higher short-circuit current for IR diodes by the factor of 4200. To solve this problem, the IR diodes were coated with an absorbing foil. In contrast, UV signals had to be amplified up to a factor of 1000.

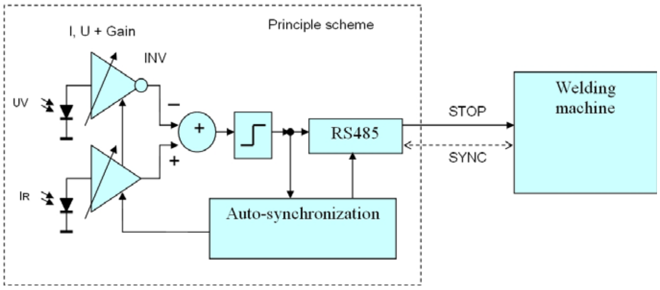


Figure 6. Signal processing of the spectral SCU.

Figure 6 shows the scheme of the spectral SCU. The light is received by the photodiodes (UV/IR, respectively) and amplified. To get the difference signal, one amplified signal is inverted and added to the other one. This signal is used for further processing [9]. The time instance when the difference signal is zero plus a predetermined delay generates a so-called STOP signal. It is used to stop the high-current phase in order to reduce the energy input into the weld seam. To avoid electric interference, a RS-485 interface is used to assign the STOP signal to the controller of the welding machine.

A prototype of the SCU was made using *s*urface *m*ount *t*echnology (SMT) on a self-developed test card. After several successful tests a *p*rinted *c*ircuit *b*oard (PCB) was designed. Figure 7 shows the final version of the sensor head with dimensions of 100 × 60 × 25 mm^3. The electrical data connectors are to the left and the photodiodes to the right side.

As a matter of course, internal signal processing allows different types of synchronization and interaction with the current of the welding machine. Therefore, two operation modes can be considered. In one mode it is possible to control the welding process by generating the start and stop conditions for the process. This mode leads to changing frequencies and pulse lengths and was not further tested. In the other mode, pulses are generated by the welding controller with a constant frequency, and the spectral SCU determines when the pulse should end by sending the STOP signal. This STOP signal holds until just before the welding machine gives the next pulse. This method leads only to different pulse lengths and was used for first experiments. Details of the electric circuit and its function of the SCU are described in [9].

Smoothed output signals and the generated difference signal are shown in figure 8. These signals reflect very well the characteristics from figure 3 even though no spectrometer with high resolution was used to deliver the input signal for the SCU. Furthermore, the photodiodes integrate over the whole arc compared to a spatially resolved area measured with the spectroscopic system.

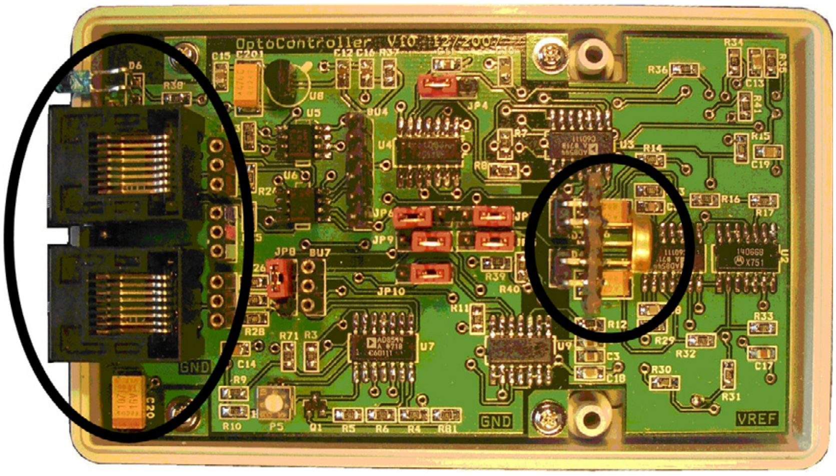


Figure 7. Spectral SCU; left circle: connectors for data transfer; right circle: photodiodes.

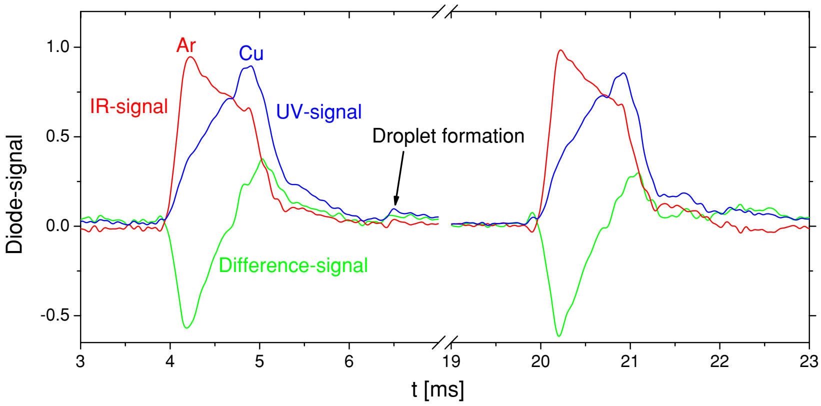


Figure 8. Photo-diode signals and difference signal during the pulsed brazing process without SCU influence [10].

So far, the results of the brazing process (CuAlZn filler wire on zinc-coated steel) were presented above. Because, the findings for the welding process with the AlMg4.5Mn0.7 are similar, the obtained results for the welding process with the influence of the SCU will be given in next section.

4. Application of the control unit

Figure 9 shows a droplet formation for a controlled welding process for different times during current pulse. Additional curves show the plot of the photo-diode signals and the STOP signal. When the SCU detects a sufficient energy input for the droplet formation, this STOP signal will be generated and sent to the welding machine controller. Therefore, it will finish the pulse earlier and avoid overshooting of the input power. After the STOP-signal fades, the power supply waits to start the next regular slope control with the predetermined frequency.

To illustrate the effect of the SCU, two weld seams with AlMg4.5Mn0.7 were made. Both had a constant weld- and wire speed, pulse frequency f and base current I_B. One weld seam was made with a pulse current of 300 A and another one with a 100 A higher current. In table 1 the main parameters are given. For the used materials, weld speed, pulse current I_P of 300 A and a pulse time t_P of around 1 ms represent the optimal setting. The SCU does not have negative influence on these setting. Using 400 A pulse current without the SCU

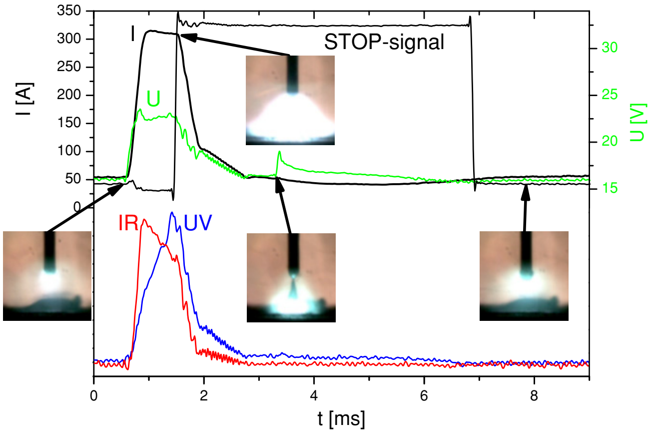


Figure 9. Pulse-welding process with droplet formation. Images show the droplet formation in dependence of current, voltage and signals of the SCU.

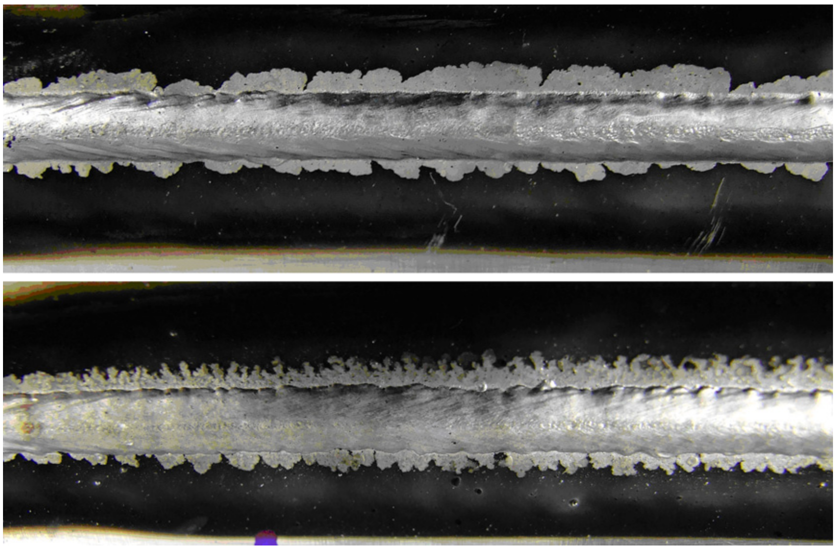


Figure 10. Weld seams made with the SCU; upper: $I_P = 300$ A optimal current; lower: $I_P = 400$ A non-optimal current.

Table 1. Main parameters for comparison of different pulse currents with the influence of the SCU.

	Optimal current	High current
Weld speed	1.40 m min^{-1}	1.40 m min^{-1}
Wire speed	3.80 m min^{-1}	3.80 m min^{-1}
f	60 Hz	60 Hz
I_B	30 A	30 A
t_P	Controlled ~1.02 ms	Controlled ~0.82 ms
I_P (A)	300	400

would destroy the work piece. In this case, the SCU detects the higher energy input into the arc and reduces the pulse time t_P. So, the energy input per unit length does not reach a critical value.

Photographs in figure 10 show both weld seams for the two settings. The upper picture shows a smoother undercut and cleaning area of the arc, which is typical for the lower current, than in the lower picture. Nevertheless these pictures demonstrate an improvement to a non-controlled process with an overload up to 30% of the pulse current I_P.

Furthermore, the flexibility of the system has to be increased by additional signal processing of the SCU. For example, it is desirable to determine the delay between the Q1 time instance when the difference signal is zero (Capture 3 section 3) and the STOP signal to avoid the necessity of a predetermination of the delay. Another aim is to upgrade the SCU with additional sensors to estimate the instantaneous weld pool temperature and correlate this with the determination of the STOP signal or even electric current adaptation.

5. Summary

Additional information from the arc was derived with the aid of a spectroscopic system and proved with a high-speed camera. A time dependence of the shielding gas and the evaporation of the metals show a characteristic spectral behaviour. The emitted lines were observed in overview spectra. Shielding-gas lines and metal lines were dominant in different spectral regions. Usage of this information is possible with different spectral-sensitive photodiodes. A fast spectral control unit (SCU) with photodiodes and an amplifier was implemented. With online data processing the diode signal is used for generating a control signal for the welding machine. Tests were carried out on a brazing (CuAlZn) and a welding (AlMg4.5Mn0.7) process. A variation of 30% of the pulse current I_P was compensated by the SCU.

Acknowledgments

This work was supported by the German Bundesministerium für Wirtschaft (BMWi) under grant AiF 14607 BG. Special thanks go to S Goecke, E Metzke and M Langula for initiating works [11]. Thanks are also given to colleagues of INP for helpful discussions during preparation of the manuscript. This work has been awarded with the ABICOR Innovation Prize in 2008.

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