WELDING RESEARCH

The GMAW Process Using a Two-Dimensional Arc Deflection with AC Hot Wires

The positioning of hot wires and signal characteristics of current intensity on the deflection pattern and weld quality is shown

BY K. SCHMIDT, E. SPANIOL, M. TRAUTMANN, J.-P. BERGMANN, AND U. FÜSSEL

Abstract

Heat input in gas metal arc welding (GMAW) directly correlates with the applied current. As a result, welding irregularities, such as incomplete fusion and excessive penetration, increase and mechanical properties decrease. One way for adjusting heat input is to use hot wire technology. In this article, a two-dimensional arc deflection in GMAW was presented by simultaneous application of two alternating current (AC) hot wires. It is shown how the positioning of the hot wires and the signal characteristics of the current intensity influenced the deflection pattern and weld quality. It was found that the magnetic fields of the two hot wires overlapped due to the narrow opening between. Therefore, an increased one-dimensional deflection resulted. To obtain a two-dimensional deflection, it was necessary to shield the magnetic fields from each other by means of a ferritic material. By pulsing or phase shifting the current signals, individual deflection patterns were possible. The effect of arc deflection was visualized with high-speed recordings and metallographic investigations. Different deflection patterns were generated to adjust heat input and counteract weld irregularities. The use of hot wire technology allowed an increase in deposition rate by simultaneous improvement of weld quality.

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Keywords

- GMAW
- Arc Deflection
- Hot Wire
- Magnetic Flux Density

Introduction

Gas metal arc welding (GMAW) is used in the steel industry, particularly in mechanical and plant engineering, rail vehicle construction, and offshore technology, due to its flexibility (i.e., from manual to fully automated application). A characteristic of GMAW is the direct introduction of filler material via the arc-conducting wire electrode, whereby an increase in deposition rate or penetration depth is inevitably accompanied by an increase in current intensity and heat input by the arc into the substrate. The high thermal stress on the base material and the weld joint results in an extensive influence on the mechanical properties, which is generally reduced. To reduce weld joint irregularities and increase weld joint quality, there have been several studies in recent years to adapt energy input in the form of an arc deflection over the surface.

GMAW processes with multiwire technologies, such as tandem welding, double wire welding, or pulsed double wire welding, should be mentioned here (Refs. 1–4). The arc is influenced by the additional arc-guided electrodes such that the energy input can be widened and the deposition rate significantly increased. The deflection of the arc, however, is difficult to individualize due to the process, so external devices, such as magnet units, are used. Yu et al. investigated a plasma-pulsed gas metal arc welding process with an additional external magnetic field (Ref. 5). Arc deflection with attached magnets and generation of deflection patterns

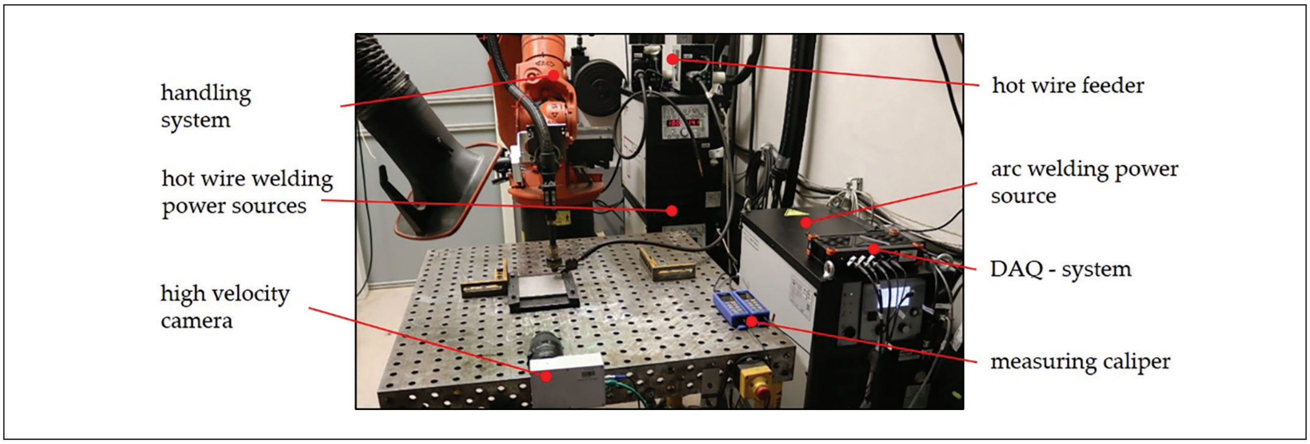

Fig. 1 — Experimental setup.

are known for gas tungsten arc welding (Refs. 6, 7). It was shown that two-dimensional patterns (elliptical, circular) can be realized and, depending on the distance to the arc, up to 260 mT may be necessary. To improve GMA root welding of pearlitic rail steel R260, Weingrill et al. used magnetic arc deflection (Ref. 8). Chen et al. investigated the influence of transverse and parallel magnetic field lines on the arc during high-speed GMAW with a three-headed-shaped compound electromagnetic field (EMF) generating device to increase welding speed and avoid weld irregularities, such as penetration notches (Ref. 9). For GMAW with a two-headed-shaped compound EMF generating device, Sharma et al. showed the relationship between the electromagnetic field and arc. Thereby, a theoretical model was set up that confirmed by experimental studies that the interaction between electromagnetic field and wire feed rate has a significant effect on heat input and aspect ratio between penetration and wetting behavior (Ref. 10).

In this context, arc deflections have always been implemented by external magnetic units, which entail a complex control effort and increased installation space. Furthermore, although the deflection allows a two-dimensional distribution of energy input, thermal stress is still too high and associated with increased weld defects. However, a more economical solution of arc deflection with simultaneous reduction of energy input is the hot-wire-assisted GMAW process. The use of additional arc-less electrodes allows the decoupling of energy input from the mass input and, thus, reduces the melt pool temperature and increases the deposition rate (Refs. 11, 12). Häßler et al. used a central filler wire in tandem GMAW to suppress interactions between the two arcs. This stabilized the dynamic weld pool and increased the deposition rate for carbon steel (Ref. 11). But the potential of a controlled arc deflection was not considered. Guenther et al. demonstrated that during hardfacing of fused tungsten carbides with additional hot wires, depending on the wire feed ratio, the thermal stress could be reduced and thus the wear resistance of the single-layer hardfacing could be increased by about 35% and the deposition rate could be doubled (Ref. 13). Suwannatee et al. further reported using a hot wire to weld 36-mm-thick K36E-TM steel plates in four layers without defects and high weld qualities (Ref. 14).

The reduction of the mean melt pool temperature by using hot wire for joint welding leads to a significant decrease of penetration and worse wetting behavior; thus, an incomplete fusion, especially incomplete root fusion. However, the magnetic field (Lorentz force) generated around the potential-loaded hot wire allows an arc deflection and control of the energy input across the area. In the case of joint welding of thick-walled components, a multilayer technique can be replaced by a single-layer technique, thus saving significant time and costs. In parallel work, the deflection of the arc by the magnetic flux density of the hot wire was simulated and verified in combination with an external magnet unit for unalloyed steels. Thereby, penetration and wetting behavior was improved significantly by a longitudinal deflection in the welding direction and an oscillating deflection transverse to the welding direction (Ref. 15).

Scope of the Investigations

In this study, arc deflection during GMAW was achieved by using two hot wires to regulate energy input and perform individual arc shapes. The magnetic fields generated around the hot wires influenced the arc. By operating the hot wires with alternating current (AC), alternating magnetic fields were created, and in combination with hot wire positioning, a two-dimensional arc deflection was achieved. The parameters affecting the magnetic flux densities of the hot wires were recorded and the resulting deflections visualized with high-speed recordings. Energy input was obtained by current and voltage measurements. Magnetic flux densities were correlated with the high-speed recordings. Finally, potential deflection patterns were analyzed, and weld joints were evaluated by metallographic investigations.

Experimental Procedures

Figure 1 shows the experimental setup. A welding power source (Alpha Q 552 Expert 2.0 puls MM, EWM AG) for the arc and two hot wire welding power sources (Tetrix 352 AC/direct current [DC] Synergic RC HW, EWM AG) were used in the experiments. The handling system was a six-axis robot (KR 15-2, Kuka Roboter GmbH) with a positional repeatabil-

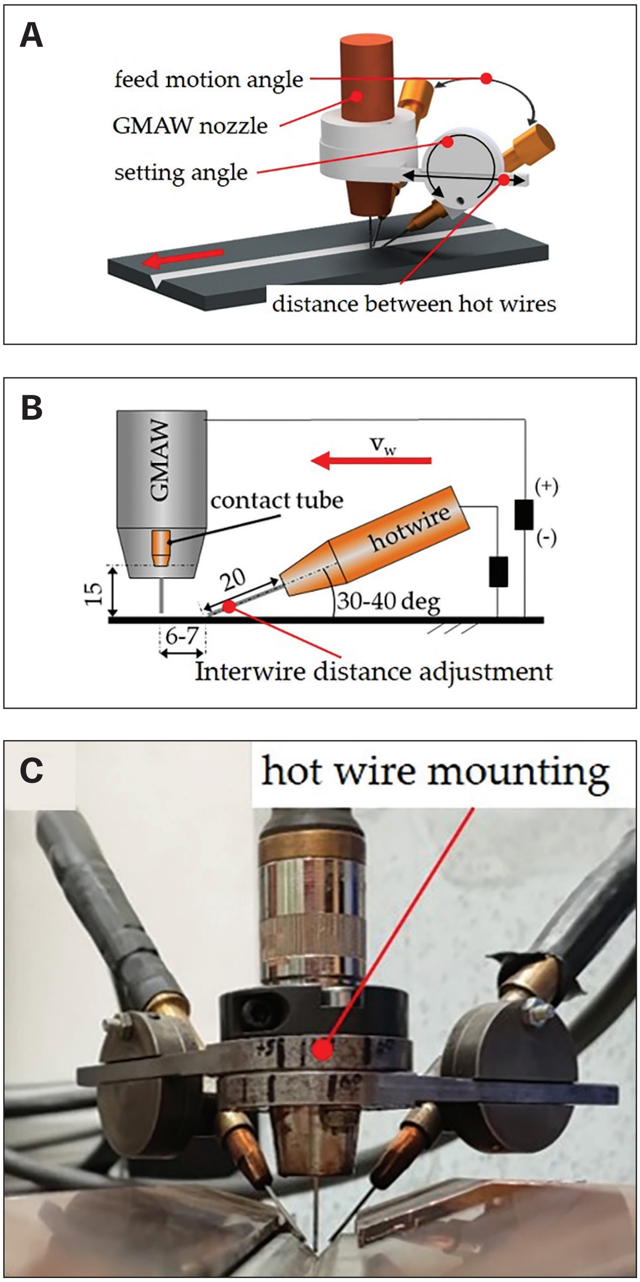

Fig. 2 — Schematic setup: A — GMAW with hot wire mounting; B — fixed parameters for hot wire positioning; C — experimental setup with hot wire mounting.

ity of 0.06 to traverse the torch and the hot wire mounting. The current-voltage waveforms were recorded with a DAQ system (Sirius, Dewesoft d.o.o.) at a frequency of 5 kHz. Measurements in AC operation were conducted with measuring calipers (CM7290 and CT7636, Hioki GmbH). High-speed recordings were performed with CamRecord CR3000×2 (Optronis GmbH) with a frame rate of 1000 frames/s and an 808-nm bandpass filter to visualize the movement of the arc.

To obtain the linear energy E_L, the process power of the GMAW process P_{GMAW} was calculated with the process power of the hot wires P_{HW1} and P_{HW2} and the welding speed v_w. The process powers were obtained from the arithmetic mean values of the measured current-voltage plots (see Equation 1).

$$E_L = \frac{P_{GMAW+HW1+HW2}}{v_w} = \frac{\overline{U_{GMAW}I_{GMAW}} + \overline{U_{HW1}I_{HW1}} + \overline{U_{HW2}I_{HW2}}}{v_w} \quad (1)$$

However, the known linear energy E_L does not consider mass input, which is why mass-related linear energy E_M was introduced for the GMAW-HW process (Ref. 13). Mass-related linear energy can be calculated from the known linear energy E_L and the applied mass $m_{GMAW+HW}$ (see Equation 2). With the help of E_M, the decoupling of material and heat input by the GMAW-HW process can be quantitatively represented.

Table 1 — Welding Parameters for Arc Deflection Investigations

Welding Parameter	Values
Welding speed v_w	840 mm/min
Wire feed rate v_{GMAW}	16 m/min
Hot wire feed rate v_{HW}	1 HW = 6 m/min 2 HW = 2 × 3 m/min
Gas flow (M12-ArC-2)	18 L/min
Deposition rate	11.75 kg/h
Welding current I_{GMAW}	380–390 A
Interwire distance GMAW	15 mm
Interwire distance HW	20 mm
Distance between GMAW and HW r	6–7 mm
Setting angle	30–40 deg
Linear energy	Approximately 1.0 kJ/mm

$$E_M = \frac{P_{GMAW+HW1+HW2}}{v_w * m_{GMAW+HW}} = \frac{\overline{U_{GMAW}I_{GMAW}} + \overline{U_{HW1}I_{HW1}} + \overline{U_{HW2}I_{HW2}}}{v_w * (m_{GMAW} + m_{HW1} + m_{HW2})} \quad (2)$$

By applying the current I_{HW} to the filler wire, a concentric magnetic field was generated around the hot wire (current-carrying, straight conductor), which is expressed by the magnetic flux density *B*. The magnetic flux density depends on the magnetic field constant μ_0 as well as on the permeability coefficient μ_s and decreases with increasing distance *r* to the hot wire (see Equation 3).

$$B_{HW} = \mu * H = \mu_0 * \mu_r * \frac{I_{HW}}{2\,\pi r} \quad (3)$$

A teslameter (FH54, Magnet-Physik Dr. Steingroever GmbH) was used to measure the emerging magnetic flux density of the hot wire. For this purpose, a transverse Hall effect magnetometer was fed laterally to the current-loaded, arcless hot wire. The measuring setup was similar to the setup in Fig. 2B, without the GMAW nozzle. Furthermore, a frequency generator (TGF4042 LXI, Aim TTi) was connected to the hot wire power source to generate different waveforms (AC/DC, trapezoidal, rectangular). Figure 2 shows the schematic (A) and the experimental setup (C) for the GMAW process with two hot wires. A self-developed hot wire mounting system was applied to mount two hot wires on the GMAW nozzle. During this study, the parameters, setting angle, distance between the hot wires, interwire distance adjustment of the hot wires, and feed motion angle were varied (Fig. 2B). Constant welding parameters are shown in Table 1.

The base material was X5CrNi18-10 in plate geometry and had a dimension of 8 × 50 × 200 mm (T × W × L). The plates were prepared with a single Y-butt joint with root face (90 deg angle, 2 mm root face). The single-pass welding of these plates in the butt joint practically represents a major challenge, since sufficient root penetration and fusion face coverage must be ensured despite wide wetting. The illustration of this extreme case is intended to demonstrate the universal applicability and performance capability of the developed high-performance process. A similar material (G19-9-LSi with a wire diameter of 1.2 mm) was used as the filler wire. Table 2 shows the chemical composition of the substrate material and filler wire.

The experimental investigations were divided into two steps. The first step was the determination of the influence of the input parameters on the magnetic flux density of the hot wire. The aim was to determine the stability of the process and its limits in order to guarantee the reproducibility of the results. In the second step, different deflection patterns were generated to deflect the arc in one dimension as well as in two dimensions. This was intended to provide an individual local energy input independent of mass input. Deflection was realized by phase shifting the hot wire AC signals. Current-voltage signals were obtained, converted to magnetic flux density, and correlated with high-speed recordings. Finally, the results were compared with metallographic sections.

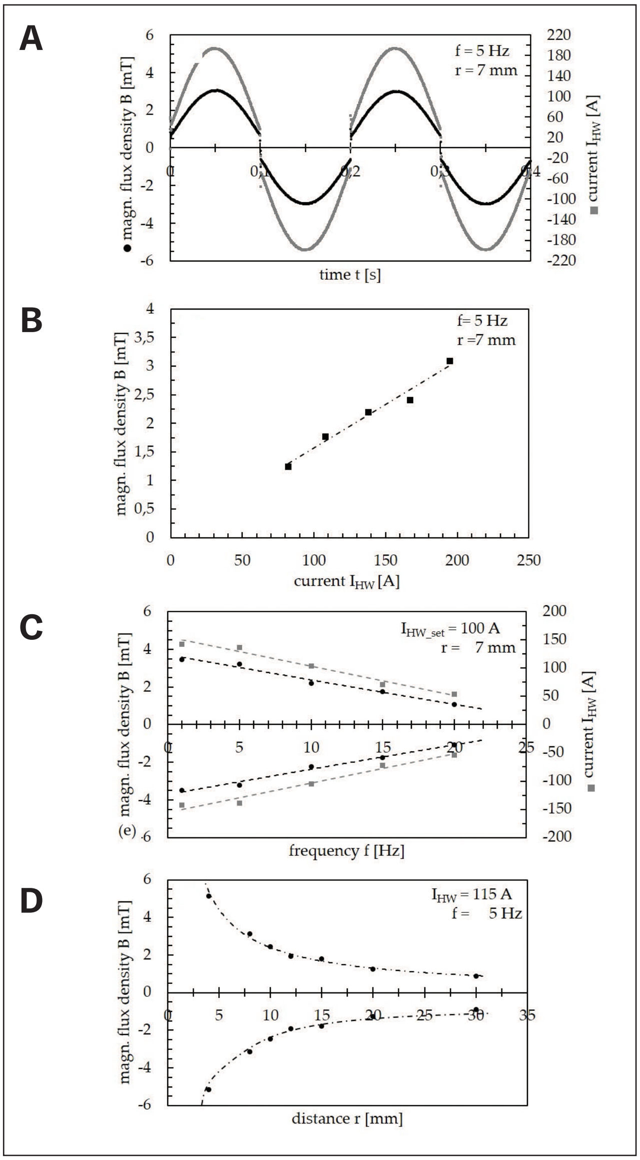

Fig. 3 — Magnetic flux characterization: A — Magnetic flux density B *as a function of the* I_{HD}*-t-plot; B — influence of hot wire current* I_{HW} *on magnetic flux density* B*; C — influence of frequency* f *on hot wire current* I_{HW} *and magnetic flux density* B*; D — decreasing magnetic flux density* B *as a function of the distance* r *to the hot wire.*

Results

Influence of Welding Parameters on Magnetic Flux Density of Hot Wire

To determine the influence of the welding parameters on magnetic flux density by the hot wire, the parameters hot wire current I_{HW}, AC frequency *f*, and distance *r* to the hot wire were varied. It was found that magnetic flux density arises in sync with the AC signal in an oscillating form (Fig. 3A), and with increasing hot wire current I_{HW} up to 195 A, the magnetic flux density *B* also increases up to 3.1 mT (Fig. 3B). Higher currents could not be measured since the hot

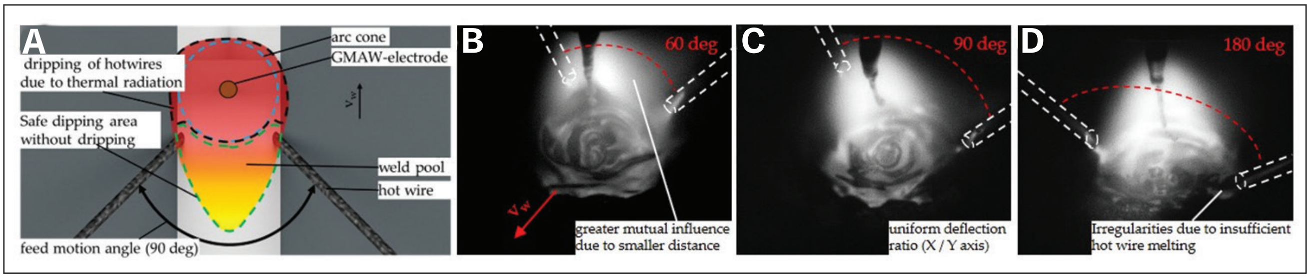

Fig. 4 — Feed motion angles for hot wires: A — Restricted plunging range of hot wires in melting pool; B — high-speed recordings for feed motion angles at 60 deg, C — 90 deg, and D — 180 deg.

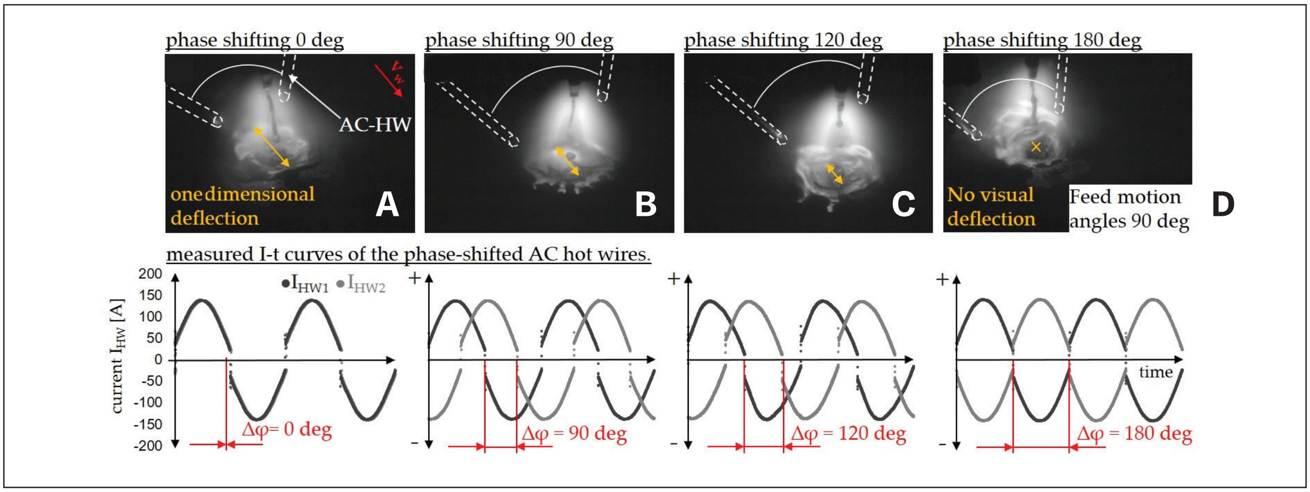

Fig. 5 — Effect of phase-shifted currents I_{HW1}, I_{HW2}, and resulting arc deflection in the GMAW-HW process with two AC hot wires.

wire melted and ignited its own arc. Further investigations showed that with increasing AC frequency *f*, the set current I_{HW_set} was reduced, and, consequently, magnetic flux density dropped by a linear rate (Fig. 3C). Such a decrease was due to hysteresis losses in the filler wire. Because of the polarity reversal, time-variable magnetic flux induces eddy currents in the conductor, according to the law of induction. These generate losses that are dissipated in the form of thermal energy, which significantly reduces efficiency. For this reason, frequencies ≤ 5 Hz were selected for the following investigations of the GMAW-HW process with AC hot wires. Thus, the greatest possible magnetic flux densities can be generated. Under constant parameter settings, magnetic flux density decreased exponentially with increasing distance *r* to the hot wire (Fig. 3D). Conversely, it can be assumed that the influence of the magnetic field is greatly reduced as the distance between the hot wire and the arc increases. To ensure process stability, the hot wires must be permanently plunged into the molten pool during the process and not drip off. Figure 4A schematically shows the limited plunging range for this purpose. Previous investigations have shown that a hot wire distance of $r = 6 - 7$ mm is reasonable, which means that a magnetic flux density of approximately 3.2 mT can be expected. The feed motion angle also contributes significantly to process stability and arc deflection. Different feed motion angles were investigated in order to generate suitable, multidimensional arc deflection longitudinal and transverse to the welding direction. It was found that angles

Table 2 — Chemical Composition of Substrate X5CrNi18-10 and Filler Wire G19-9-LSi (%)

Material	C	Si	Mn	P	S	Cr	Ni	N
X5CrNi18-10	≤ 0.07	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.030	17.5–19.5	8.0–10.5	0.1
G19-9-LSi	≤ 0.025	0.9	1.8	≤ 0.025	≤ 0.015	20	10.5	0.06

< 90 deg revealed a very distinct deflection longitudinal and less transverse to the welding direction v_w as the transverse component of the magnetic flux density was too low (compare Fig. 4B). Feed angles > 90 deg were not suitable for the GMAW-HW process as the filler wires were insufficiently dipped into the weld pool, mainly resulting in process instabilities, such as contact failure or feed errors (Fig. 4D). Thus, an infeed angle of 90 deg was used to achieve a uniform ratio between longitudinal and transverse deflection while ensuring process stability (Fig. 4C).

Influence of Phase Shifting on Arc Deflection for AC Hot Wires

Next, the phases of the AC current signals were shifted to create a multidimensional arc deflection. Due to the phase shift, different current amplitudes and, consequently, different magnetic flux densities were applied to the hot wires as a function of time to generate a dynamic oscillation longitudinal and transverse to the welding direction. Figure 5 shows high-speed recordings for phase shifts of $\Delta\varphi$ (A) 0, (B) 90, (C) 120, and (D) 180 deg and the corresponding current-time plots of the single hot wires HW1 and HW2. The feed angle was 90 deg. At a phase shift of $\Delta\varphi$ 0 deg, a very strong, one-dimensional oscillation occurred longitudinal to the welding direction. With an increasing phase shift of up to 180 deg, the one-dimensional oscillation decreased until the arc cone was no longer visibly deflected. This was due to the accumulation of the single magnetic fields. If the currents I_{HW1} and I_{HW2} have the same polarity, the magnetic fields add up (compare Fig. 5A). If the current amplitudes I_{HW1} and I_{HW2} have different signs, the magnetic fields are subtracted (compare Fig. 5D).

To prevent the accumulation of magnetic field lines, an isolator was installed between the hot wires. The isolator consisted of a high ferrite material. By separating the magnetic field lines, two individual magnetic fields were generated, which can cause the arc to oscillate diagonally (feed motion angle = 90 deg) to the welding direction. By means of a phase shift, the individual oscillations can be combined to form a two-dimensional deflection pattern. Figure 6 shows a two-dimensional arc deflection in the form of a rotating arc cone. The measured current-time plot with a phase shift of $\Delta\varphi = 120$ deg is shown and characteristic positions are marked (Fig. 6A). The AC frequency f was 5 Hz and the maximum current amplitude was set to 210 A. Represented is a phase section of $\Delta t = 150$ ms. In position 1, $I_{HW1} = +208$ A had its maximum and attracted the arc significantly closer (Fig. 6B). Due to the deflection of HW1 and the resulting larger distance to HW2, the repulsion due to the negative polarity ($I_{HW2} = -173$ A) was only slightly observed. In the further course, magnetic flux density of HW1 decreased due to the decreasing current I_{HW1}. At position 2, the HW1 was briefly currentless due to the polarity reversal, so that the magnetic flux density B_{HW1} was nearly 0 mT. Due to the already positively poled HW2 with $I_{HW2} = +147$ A, the arc moved onto HW2 (Fig. 6C). At position 3, the arc was strongly repelled in a welding direction by HW1 ($I_{HW1} = -210$ A) and simultaneously attracted by the positively poled HW2 ($I_{HW2} = +187$ A). As a result, the arc deflected diagonally in the welding direction (compare Fig. 6). At position 4, the polarity of HW1 reversed again. Thus, the arc was strongly repelled by $I_{HW2} = -139$ A.

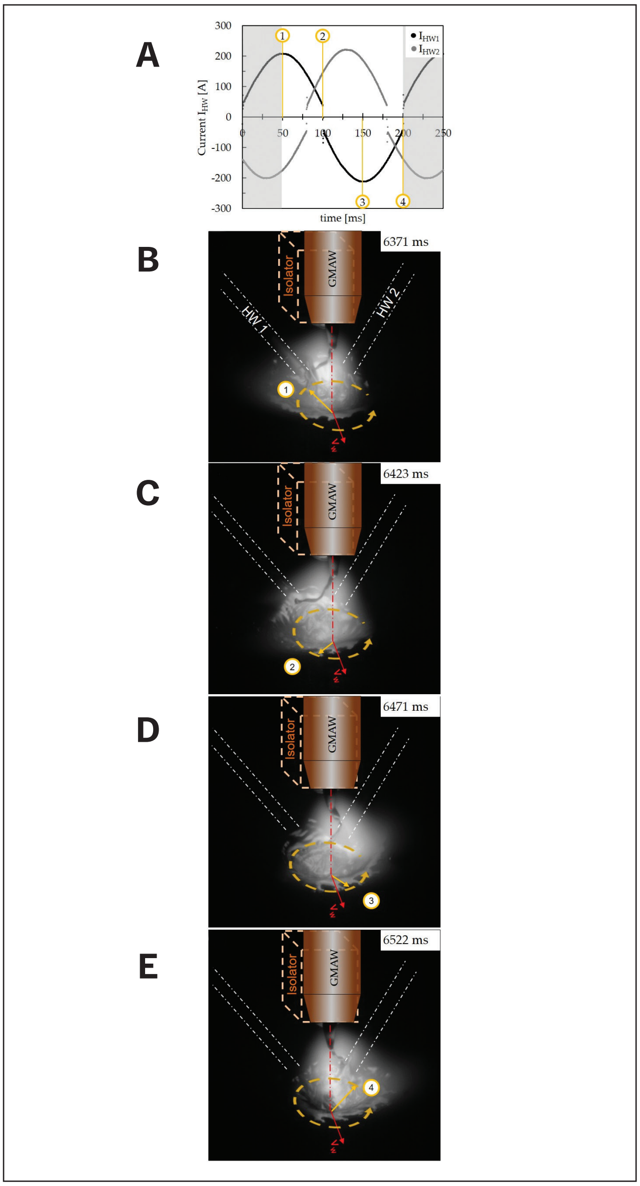

Fig. 6 — A — Two-dimensional arc deflection recordings — I-t plot of the phase-shifted AC hot wires with φ = 120 deg, f = 5 Hz and characteristic deflection positions 1–4; B — two-dimensional, circular arc rotation in the GMAW-HW process with two phase-shifted hot wires (φ = 120 deg) using magnetic shielding by a ferritic material (isolator).

Influence of Arc Deflection on Welding Geometry

The influence of two-dimensional arc deflection on weld geometry was determined by metallographic analysis. One-dimensional arc deflection (GMAW-HW with one DC hot wire) was compared with two-dimensional arc deflection (GMAW-HW with two AC hot wires). As weld preparation, single-pass bead-on-plate welds were compared with

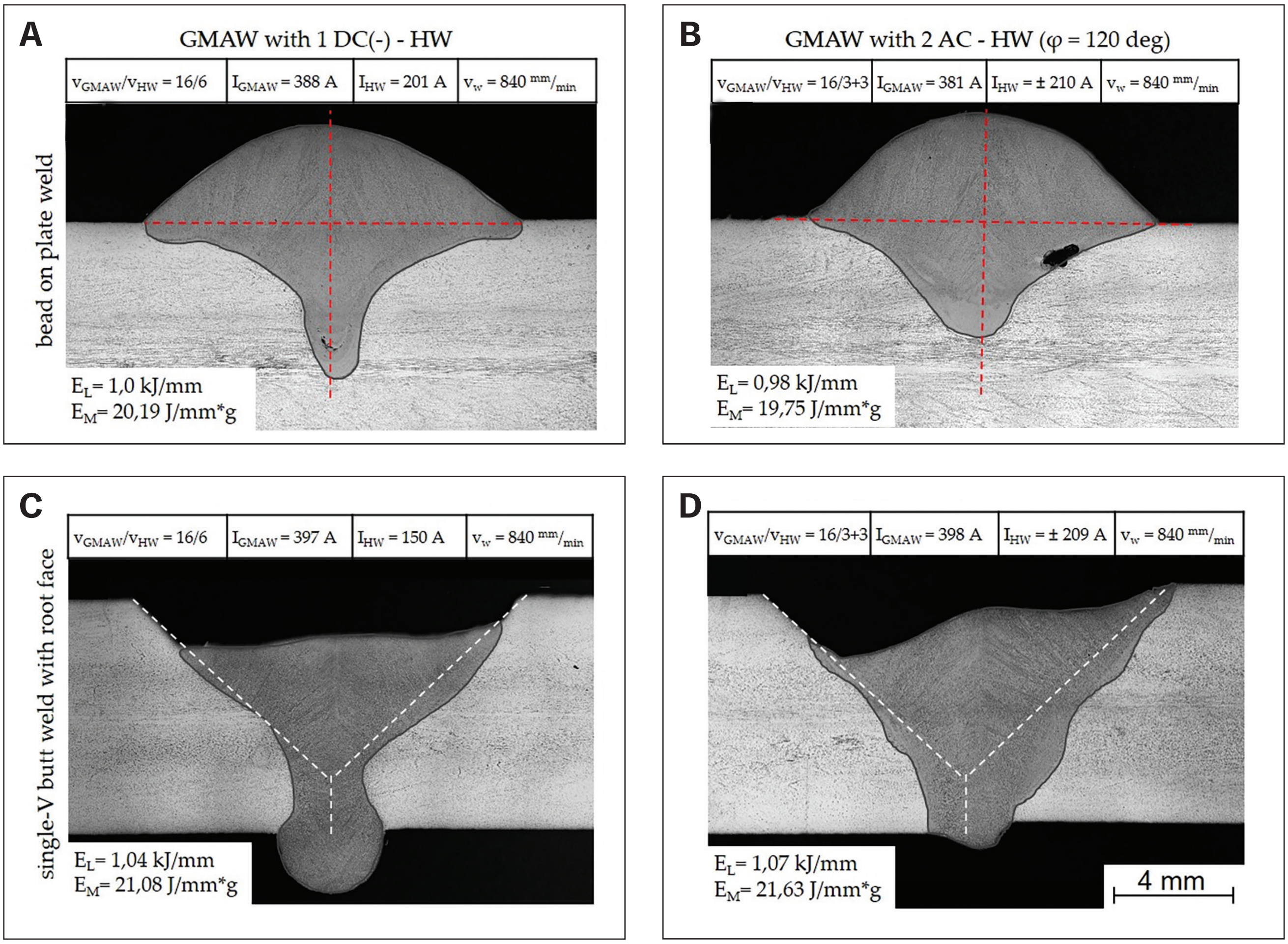

Fig. 7 — Comparison between the GMAW-HW process with one DC hot wire and GMAW-HW process with two phase-shifted AC hot wires (φ = 120 deg) for constant line energy E_L based on the example of bead-on-plate welds (A, B) and single-V butt joints with root face (C, D).

single-pass V-butt joints with root face. For a direct comparison of the processes, the linear energy $E_L = 1.0$ kJ/mm and the mass-related energy $E_M = 20 - 22$ J/(mm*g) were kept constant. A significant reduction in penetration depth was observed for the bead-on-plate welds (compare Figs. 7A, 7B). The increased heat input transversely to the welding direction due to arc rotation led to an enlarged root width. The wetting behavior for melt runs remained unchanged to a minor extent. As a result, the widening of the heat input into the sidewalls counteracted an excessive penetration (compare Fig. 7C) and produced a better sidewall fusion (Fig. 7D).

Discussion

The Relationship between Hot Wire Polarity and Arc Deflection

The results show that the arc can be deflected by simply applying a current to the filler wire. The physical explanation is based on a local density difference of the magnetic flux lines. Considering Fig. 8A, the GMAW electrode and hot wire electrode are contrastively polarized. Thus, an increased magnetic flux density is generated between the electrodes, which has a dominating effect. In the case of anodic polarity of the hot wire, the magnetic flux lines between the GMAW electrode and hot wire (+ΔB) accumulate, and the moving charge carriers (v_{e-}) in the arc plasma are deflected in the welding direction in this example, according to Lorentz's left-hand rule. When the experimental setup was upgraded with the second hot wire, the arc was visibly deflected in only one dimension, despite varying parameters. This effect is explained by the addition of the individual magnetic field lines around the two hot wires. This effect can be compared with the Lorentz force between two current-carrying conductors aligned parallel to each other. If the magnetic fields are in the mutual area of action, the field lines overlap. While electrodes with the same polarity strengthen the magnetic field around the hot wires, electrodes with different polarity weaken the magnetic field. Based on Equation 3, both magnetic flux densities B_{HW1} and B_{HW2} sum up to a common magnetic flux B (see Equation 4).

$$B = B_{HW1} + B_{HW2} = \mu_0 * \mu_r * \left(\frac{I_{HW1}}{2\,\pi\, r_{HW1}} + \frac{I_{HW2}}{2\,\pi\, r_{HW2}}\right) \quad (4)$$

Thus, a local increase of magnetic flux density (++ΔB) can be expected between the three electrodes with the same

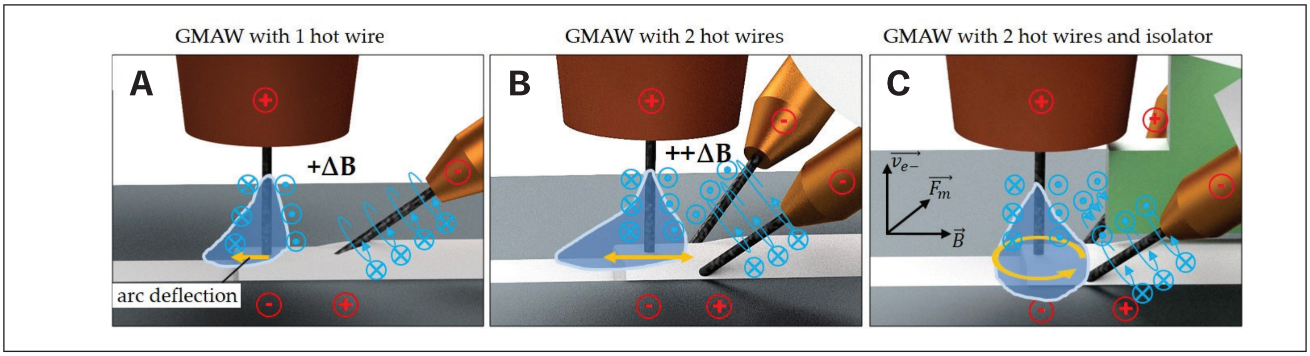

Fig. 8 — Schematic magnetic field lines during the GMAW-HW-process: A — One hot wire; B — two hot wires; C — two hot wires with isolator.

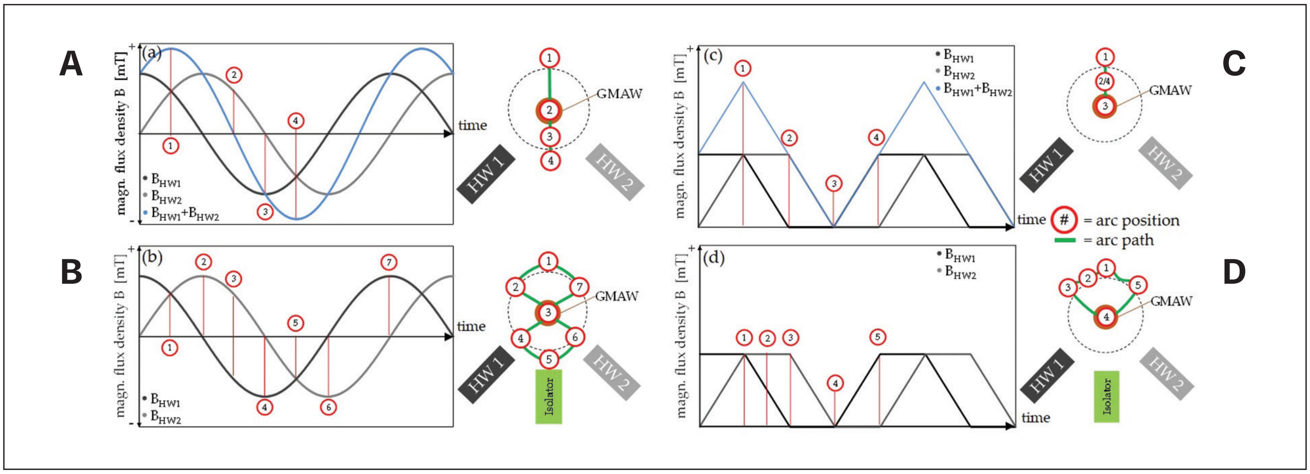

Fig. 9 — Schematic signal plot of the magnetic flux densities B_{HW1}, B_{HW2} applied to the hot wires HW1, HW2, and corresponding arc paths and arc positions: A — Sinusoidal AC signals; B — sinusoidal AC signals with isolator; C — trapezoidal DC signals; D — trapezoidal DC signals with isolator.

polarity (compare Fig. 8B). This effect can be used for an amplified, stationary, one-dimensional deflection (DC) or a one-dimensional oscillation (AC) along the welding direction. Depending on the phase shift of the AC signals, the difference of magnetic flux density (++Δ*B*) can be minimized in such a way that arc deflection can also be completely suppressed (compare Fig. 5). It must be mentioned that a distortion of the magnetic field lines due to surrounding ferritic materials cannot be excluded. However, this could not be proven during the investigations. Losses due to field line curvature in the direction of the substrate were initially accepted. A two-dimensional deflection requires at least two independent magnetic fields. Consequently, a ferritic material is positioned between the hot wires as a magnetic shield. Due to the high difference in permeability between air ($\mu = 1$) and iron ($\mu = 2000 \ldots 5000$) (Ref. 16), obliquely incident magnetic field lines are deflected almost parallel to the ferritic material. The superposition of the magnetic fields is interrupted, and different two-dimensional deflection patterns can be generated, depending on the applied current and the positioning of the hot wires (Fig. 8C).

Relationship between Current Waveforms and Arc Deflection

The obtained results show that arc deflection occurs depending on the current value and the phase shift. The theoretical path followed by the arc during magnet-induced deflection is now to be illustrated. Figure 9 shows the schematic *B — t* diagrams with the corresponding figure sketches. Figure 9A schematically shows two sinusoidal AC signal waveforms (B_{HW1}, B_{HW2}) with a phase shift $\varphi = 120$ deg, which are generated by the hot wires *HW1* and *HW2*. As shown in Fig. 5, in such a setup, the magnetic fields overlap and form a common magnetic field (*BHW1* + *BHW2*), according to Equation 4. Based on the characteristic positions, it can be seen that the arc performs a one-dimensional deflection along the welding direction (arc path). This distributes the heat input along the welding direction, which improves joint preheating and wetting behavior. If, as in Fig. 6, a magnetic shield (isolator) is positioned between the hot wires, two individual magnetic fields will be active. Depending on the polarity of the current, the arc is attracted or repelled by the individual hot wire (compare arc positions in Fig. 9B). The resulting two-dimensional deflection pattern corresponds to a pendulum movement along the welding direction with a clear transverse component to the welding direction in the shape of an 8. Consequently, the heat input transverse to the welding direction is increased, which may improve sidewall fusion and wetting behavior.

DC signals are particularly suitable for one-sided deflection. Figure 9C shows two offsets: trapezoidal signal waveforms of the hot wires *HW1* and *HW2*, which produce a cumulative triangular signal due to a missing magnetic shielding. Without a polarity change, the arc oscillates just one-dimensionally in front of the weld pool. Thus, a more intensive joint preheating or a lower thermal stress of the melt pool is achieved. In combination with a magnetic shield, an almost elliptical, two-dimensional deflection in welding direction is obtained and, in addition, sidewall fusion is improved (compare Fig. 9D).

Conclusion

By using hot wire in GMAW, different deflection patterns can be generated. The following conclusions can be obtained:

1) The positioning of the hot wires is crucial for process stability and applied magnetic flux density.

2) If the polarity of GMAW and hot wire are the same, the arc is deflected in the welding direction by the dominant magnetic flux density. If the polarity is inverse, the arc is deflected against the welding direction.

3) If the individual magnetic fields of the hot wires are not shielded from each other, they add up and form a common magnetic field. This results in a one-dimensional arc deflection. Depending on the operating mode, static deflection (DC) or oscillation (AC) can be generated.

4) By magnetic shielding of the individual magnetic fields, a two-dimensional arc deflection can be generated. Depending on the operating mode (DC/AC) and the current signal (sine, trapezoidal, etc.), application-dependent deflection patterns can thus be realized.

Arc deflection allows adjusting the heat input area-wise into the workpiece. In combination with hot wire technology, it is possible to counteract weld pool overheating or weld imperfections, e.g., incomplete sidewall fusion or excessive penetration, resulting in an improvement in weld joint quality and an increase in deposition rate or mechanical properties.

Acknowledgments

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KIRIL SCHMIDT (*kiril.schmidt@tu-ilmenau.de*) and **JEAN PIERRE BERGMANN** are from the Production Technology Group of Technische Universität Ilmenau, D-98693 Ilmenau, Germany. **ERIC SPANIOL**, **MARCUS TRAUTMANN**, and **UWE FÜSSEL** are from the TU Dresden, Faculty of Mechanical Science and Engineering, Chair of Joining Technology and Assembly, Institute of Manufacturing Technology, Dresden, Germany.