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Modelling of Welding Systems with Arc Controlled by the Magnetic Field – Part 1: Technological Effects of External Magnetic Fields

Abstract: Today's welders are in great need of knowledge concerning the magnetic field on the electric arc. On one hand, the aforesaid effect on welding arc is detrimental as it causes the so-called magnetic blowout and necessitates undertaking actions and measures aimed to counteract such a phenomenon. However, on the other hand, the magnetic field can be used to improve the quality and increase the efficiency of welding processes. The magnetic field effect on the arc leads to the deflection and changes in the shape of the latter.

Key words: magnetic field, welding arc, magnetic blowout, welding efficiency

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1. Introduction

Technological operations such as joining and cutting usually require high heat concentration. For this reason, it is often necessary to use special measures and methods favouring the compression of the arc column and stabilise the position of the spot on the surface of an element or structure. On the other hand, in terms of other technological processes, the use of intense heat flux generated by the arc is sometimes inconvenient. This is particularly the case of operations involving the heating or melting of the surface layers of large areas of metallic elements. In such situations, deconcentrated heat is responsible for a significant increase in the weld pool area, the widening of the seam of elements (e.g. made of aluminium) and making the weld pool shallow. It is also possible to obtain increased efficiency of plasma surfacing, hardening, spraying, etc.

The use of additional magnetic fields enables the non-contact and operational quality control of welding processes (e.g. joining and surfacing). The issue of magnetic field-controlled welding arc is a research area concerning high-performance and precise additive (laminar) production.

Depending on the needs, the magnetic control of the electric arc is applied in cases of varied electrode polarity, the use of direct or alternating current as well as various shapes and frequencies of current waveforms. Induction coils are also powered by various currents [1].

In terms of direct current (DC), when the electrode is connected to the positive pole, such a polarity type is designated as DC electrode positive (DCEP). In turn, when the electrode is connected to the negative pole, the polarity is designated as DC electrode negative (DCEN).

The vast majority of Gas Metal Arc Welding (GMAW) applications involves the use of DCEP. This type of polarity results in a lower welding arc temperature, responsible for the overly low weld bead penetration. The aforesaid conditions provide stable arc burning, smooth metal transfer, relatively low spatter, favourable weld bead characteristics and deep weld penetration within a wide range of welding currents. In terms of DCEN, on the contrary, the sizes of molten metal droplets tend to increase, whereas the transfer of droplets becomes irregular, increasing the spatter of large grains. For this reason, DCEN necessitates the development of appropriate filler metal wires of unique chemical composition, providing excellent welding efficiency of galvanised sheets/plates [2].

Part 1 of the article contains an overview and constitutes an introduction to the following parts, including those concerned with the modelling and computer simulation of systems with magnetic field-controlled arcs.

2. Detrimental magnetic field effect on welding arc

In arc welding, a common issue is the phenomenon of magnetic blowout. Usually, the magnetic field of the arc has a negative effect on weld formation. It is also possible to observe the deterioration of arc spatial and physical stability, resulting from the uncontrolled deflection of the plasma column and dependent on the method of connecting the arc powering system and the presence of ferromagnetic elements in its vicinity.

The actual reason for magnetic blowout is the interaction of two magnetic fields, i.e. the magnetic field of the current flowing through the electrode and arc and that of the current flowing through elements subjected to welding. In addition, nearby ferromagnetic elements may affect the arc, causing its deflection. Such a phenomenon results from the greater magnetic permeability of ferromagnetic materials (thousands of times) if compared with that of air. An additional reason for the blowout may be the residual magnetism of ferromagnetic elements subjected to welding, e.g. following the performance of

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non-destructive diagnostic tests. Figure 1 presents various cases of welding arc column deflection.

Technological operations such as joining and cutting usually require high heat concentration, necessitating the use of special measures and methods aimed at compressing the arc column and stabilise the position of the (anode) spot on the surface of an element or structure. Appropriately formed magnetic fields can be used to focus or defocus arc plasma.

3. Protection of the welding arc against the detrimental effect of the magnetic field

A frequent objective concerned with the organisation of the welding system design is the achievement of the spatial and physical stability of arc discharge, necessitating the elimination of magnetic blowout. The effectiveness of such actions is most visible after performing qualitative (e.g. magnetic) tests of joints.

An issue is the presence of residual magnetism of elements, usually after the performance of magnetic tests. Activities preventing the adverse effect of the magnetic field include the demagnetisation of elements before welding, compensation by means of the magnetic field directed opposite, the magnetic screening of the welding zone, magnetic field shunting and the separation of elements using special plans for supplying current to a given product. However, demagnetisation entails the application of special equipment, the use of which can be inconvenient as the process itself is time-consuming, reduces efficiency and requires high qualifications of the personnel.

Because of the fact that the direction of welding arc deflection depends on the polarity of the external magnetic field, it is advisable to use alternating current to stabilise the welding process of magnetised elements. In addition, it is advantageous to use the rectangular waveform as it facilitates the control of parameters such as amplitude and frequency.

The methods enabling the elimination of magnetic blowout are as follows:

a) electrode deflection,

b) use of high-frequency alternating current,

c) change of the currently used power supply point.

The reverse polarity arc is more stable than that of the direct polarity. The conditions described in publication [4] enabled the obtainment of high-quality welds.

The rectangular current waveform is used during non-consumable electrode argon arc welding, automatic welding under flux and gas metal arc welding.

If the induction of the magnetic field in the electrode gap changes within the range of 0 mT to 100 mT, it does not affect arc ignition with the contact method. An increase in the frequency of rectangular alternating current leads to an increase in the electrode gap distance after arc termination, a decrease in the angle of arc column deflection from the electrode axis and the reduction of the molten metal bridge (Fig. 2). An increase in the frequency of the above-named current within the range of 50 Hz to 500 Hz triggers a significant increase in the physical and spatial stability of the arc. A decrease in deflection angle α takes place as a result of plasma inertia and reduces an increase in the column length.

However, a change in the frequency of the magnetic field leads to the obtainment of the (strongly nonlinear) characteristic presented in Figure 3 [5]. If the frequency of field changes is low, the amplitude of the anode spot displacements is high and the changes in the column length are also significant. If the frequency is excessively high, the anode spot becomes still and only the central part of the plasma column undergoes slight deformation.

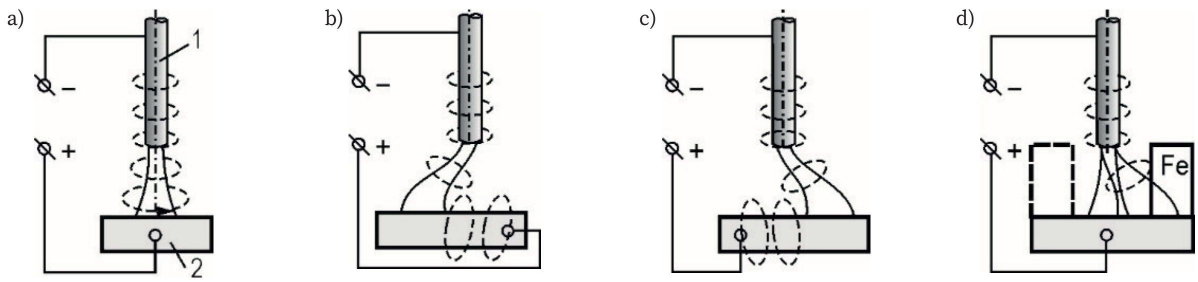

Fig. 1. Method of connecting ferromagnetic elements and its effect on welding arc deflection (1 – electrode and 2 – element subjected to welding) [3]

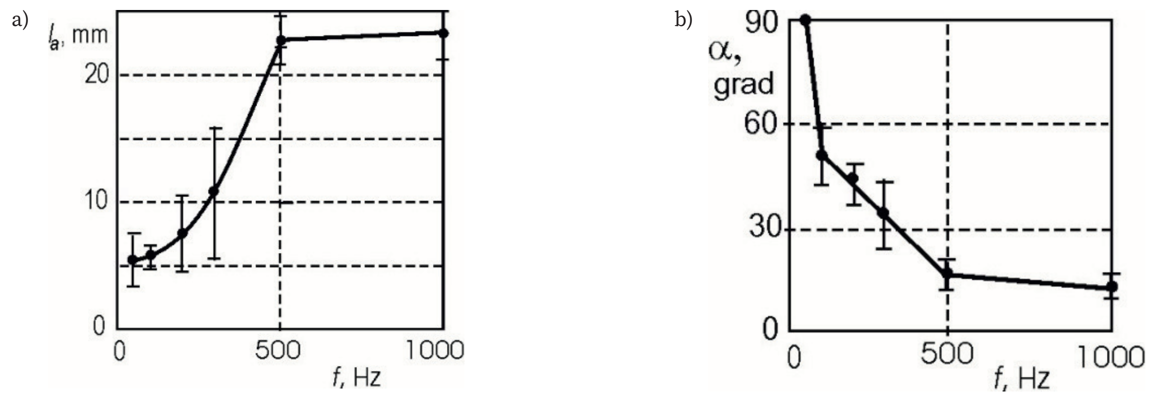

Fig. 2. Effect of the frequency of rectangular alternating current on a) electrode gap after arc termination in the zone of the transverse magnetic field and b) angle of deflection α from the arc column (B = 100 mT) [4]

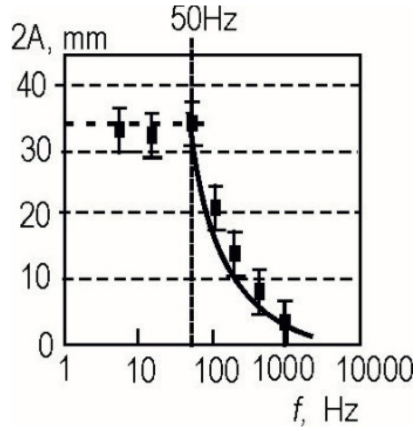

Fig. 3. Measured oscillation width of the 2A arc plasma column

4. Elimination of magnetic blowout in welding processes

The elimination of magnetic blowout in welding processes involves the use of the following [6]:

a) non-magnetic materials,
b) magnetic clamps or terminals,
c) additional magnetic screens,
d) additional magnetising coils.

Publication [3] discusses a method where magnetic blowout is used to control the welding process (see Figure 4). However, such a solution entails the use of a special KZ commutation system to smoothly switch the conduit from the power supply source to the appropriately arranged terminals on elements subjected to welding. If the power supply source is connected alternately at points 1, 2, 3 and 4, arc 5 will deflect in the direction of arrows A, B, C and D presented in Figure 4 and the sequence of deflection will be clockwise. If the sequence of connecting the power supply source is changed to the opposite (1, 4, 3, 2), the arc will rotate counterclockwise.

Figure 5 presents examples of eliminating residual magnetism, which, during the welding of structures made of steel sheets/plates, could trigger the magnetic blowout. The case of one transformer use includes Figures 5a and 5b. Figure 5c presents the use of two transformers, whereas Figure 5d presents the use of up to three transformers. The transformers can be powered from a 50 Hz network. The Author of the patent suggests the use of transformers from resistance welding machines.

Figure 6a presents how to eliminate the residual magnetism of tubular elements. The presence of the magnetism could trigger the magnetic blowout during the welding of a side gap. Figure 6b presents how to prevent the magnetic blowout during the welding of two steel tubes.

The selection of a system for eliminating the magnetic blowout depends on the shape and size of elements subjected to joining. The transformers supplying the elements are switched on at full power. After a short time (between 1 and 2 seconds), the current is reduced and the transformers are switched off completely. In order for the appropriate circuits to be closed and enable the flow of current, it is necessary to clamp jumpers or the elements must be temporarily welded in some places. It should be noted that the demagnetisation of the elements using the above-presented methods is relatively complex and expensive.

The elimination of residual magnetism in long elements made of steel (e.g. pipes, rods) can be performed using sliding magnetic inductors. If the inductors are made of flexible wires, the shape of the former can be easily modified to adjust them to the shape of the elements being clamped. In order to obtain the zero value of induction in the gap between the tubes, the Authors of publication [8] suggest powering the inductors with DC characterised by the same

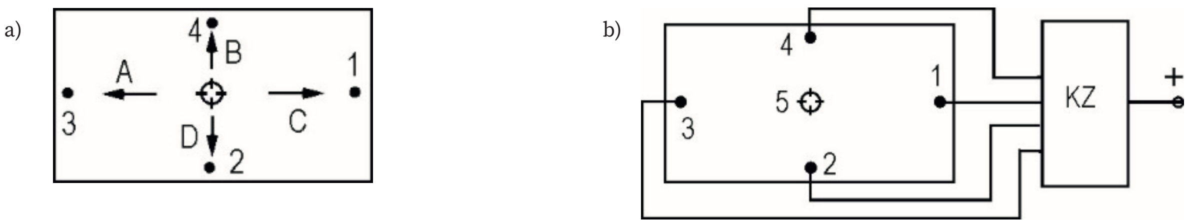

Fig. 4. Schematic diagram of the power supply of ferromagnetic elements at four points (KZ – commutator and 5 – electrode spot of electric arc) [3]

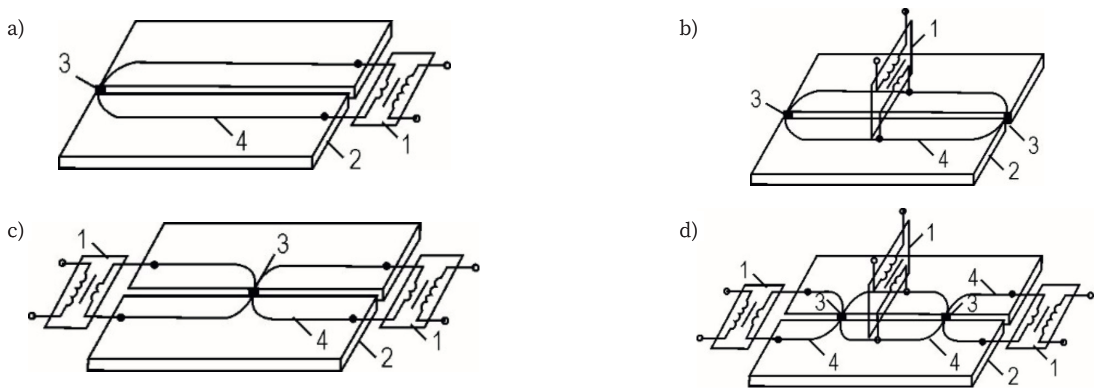

Fig. 5. Schematic diagrams of systems for eliminating the magnetic blowout effect during the welding of steel sheets/plates: a) and b) with one transformer, c) with two transformers and d) with three transformers (1 – single-phase transformer, 2 – element subjected to welding, 3 – jumper and 4 – current flow circuit) [7]

Fig. 6. Schematic diagrams of systems for eliminating the magnetic blowout effect during the welding of tubular elements (1 – single-phase transformer, 2 – steel tube, 3 – jumper and 4 – current flow circuit) [7]

Fig. 7. Schematic diagrams of systems for eliminating residual magnetism in long elements made of steel: a) using two inductors and b) using one inductor (1 – tubular elements, 2 – magnetic inductors and 3 – power source)

value. However, a similar solution might involve the powering of the inductors with decaying AC.

The use of direct current for the welding of ferromagnetic elements can re-magnetise them. In the systems presented in Figures 5 and 6, the galvanic insulation of the power supply sources and the low value of their output voltage enable the simultaneous operation of the systems for the elimination of the magnetic blowout and the welding systems. The system presented in Figure 7 provides more reliable insulation of the power supply sources.

5. Limitations of the technological use of arc without additional magnetic field-based control

One of the significant disadvantages of argon-shielded arc welding is the small number of control parameters, including welding current, welding rate, arc column length and gas mass stream. The foregoing affects the width, depth and height of the weld [9]. In addition, the shortage of skilled labour necessitates the search for improvements based on mechanised or automated welding techniques.

The precision and speed of spot location control through electrode or torch movements could be insufficient to satisfy the needs of various technological operations. Usually, during welding, the arc travel rate should correspond to that of electrode melting (depending on current, electrode diameter, electrode melting rate, weld type, etc.). In robotic welding, the arc travel rate is nearly tenfold higher than that of manual welding (6-7 mm/min). In surface processing technologies, the forward (and particularly sideward) arc travel rate can be many times higher (by using the variable magnetic field).

Under actual conditions, the temperature distribution in the cross-sections of the low-temperature plasma beam is irregular. The temperature on the axis of the plasma beam is usually several times higher than its average mass temperature [10]. The quality of welded joints is determined by the depth of heat penetration, which can be increased by increasing the value of the welding current. However, such a solution could intensify welding imperfections such as deformations of elements.

Stainless steels are characterised by significant thermal expansion and low thermal conductivity, frequently leading to the deformation of elements made of such steels. However, the greater the plate thickness, the smaller the deformations [2]. Because of their lower specific gravity, magnesium alloys are increasingly often used in car manufacturing. The issues accompanying the performance of gas metal arc welding processes (GMAW) include weld deformations and significant spatter.

Conventional arc is inconvenient as regards the heating and melting of the surface layer over a large area. This is also necessary for hardening, surfacing and spraying. Arc plasma pressure-related forces combined with electromagnetic forces, the weight of the weld and the surface tension of the liquid, lead to the formation of unfavourably-shaped welds characterised by convexity on the underside of the structure.

Low-temperature plasma flows are widely used in surface engineering technologies, i.e. surfacing, sputtering, hardening, etc. Some material processes, including plasma arc cleaning and surface processing involving the use of plasma arc, do not require a concentrated heat source, yet they require the use of a uniform and controlled plasma arc.

Plasma arc cutting (PAC) has become one of the most commonly used thermal cutting methods, the reasons being high efficiency, a wide range of applications and small thermal deformations. The farther the arc is from the plasmatron nozzle, the greater the influence of external air, triggering arc divergence and reduced cutting efficiency.

The arc-based welding process or heat treatment combined with an additional magnetic field is characterised by the simplicity of the additional device, low investment and operating costs, lower energy consumption, etc.

6. Additional magnetic field effect on electric arc

The notion of the magnetic field effect on the welding process involves changes in arc discharge conditions, electrode metal transfer and the conditions of primary crystallisation of the metal in the weld pool.

Depending on the position of the field in relation to the axis of the welding arc, it is possible to obtain various types (i.e. longitudinal and transverse) of external magnetic fields. The lines of the forces of the longitudinal magnetic field are parallel to the axis of the welding arc, whereas the lines of forces of the transverse magnetic field are perpendicular [11].

Under industrial welding conditions, it is difficult to obtain longitudinal and transverse magnetic fields close to the ideal, and even more difficult to obtain uniform magnetic fields. Transverse magnetic fields are characterised by the greatest potential for controlling the welding arc and the formation of metal welds. In turn, longitudinal magnetic fields have the greatest potential for controlling the primary crystallisation of metals.

Depending on the type of current supplied to the induction coil, it is possible to obtain various (i.e. constant or variable) types of magnetic fields. In the latter case, the coil can be powered by unipolar or bipolar current characterised by sinusoidal, triangular, rectangular and other waveforms. The external magnetic field interacts with the plasma and the magnetic field of the arc. In the magnetic field, plasma behaves like a diamagnetic substance.

Controlling the electric arc using the magnetic field has an advantage over controlling the former by changing the position of the electrode or that of the gas mass stream. The reason for the aforesaid situation is the low inertia of the first process [12]. Calculations of the arc with magnetic deformation are significantly more complex in comparison with those concerning the arc in the field with magnetic displacement.

By affecting the welding arc magnetically, it is possible to obtain the following [13]:

1) control arc plasma (cathode and anode) beams,
2) form variedly shaped and sized arcs,
3) control the position of electrode spots;
4) form welds of varied thickness and width,
5) control joint crystallisation in the weld pool.

The variable external cusp magnetic field (ECMF) can compress the arc. The currents of the electromagnets with poles close to the plasma column directly affect the ellipticity of the arc cross-section, whereas the frequency of changes affects arc contraction. The controlled contraction of the arc in the external magnetic field is triggered by Lorentz force. The additional contraction of the arc with the nozzle improves precision and enables the obtainment of high efficiency [14]. The effect of the arrangement of the four poles of the magnetic system on the shape of the cross-section of the arc plasma column is presented in Figure 8.

The practical implementation of the external magnetic field control of the electric arc is usually used in welding machines with the dependent arc. The plasma column of such a discharge is either entirely or mostly located in the free area between the electrode and the workpiece. This applies to welding with the electrode or plasma torch with the electrode close to the outlet or even protruding out of the nozzle.

In plasmatrons with internal electrodes, the arc is independent and usually burns only inside the discharge channel between the cathode and the anode. However, if the discharge parameters (primarily current, gas mass stream and nozzle hole diameter) are properly adjusted, the arc can form a loop and partially protrude out of the nozzle. Moving gas ions and metal vapours are blown out of the nozzle (outside the plasmatron). In such a case, the external magnetic field can affect the protruding part of the arc.

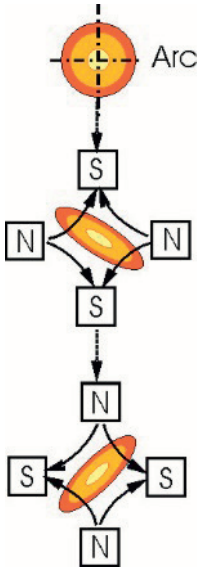

Fig. 8. Deformation of the arc column cross-section triggered by changes in the magnetic field

The shape of the welding arc can be modified depending on the configuration of the external magnetic field. Based on various configurations, the electromagnetic field can be classified as cup magnetic field (CMF), axial magnetic field (AMF), longitudinal magnetic field (LMF), transverse magnetic field (TMF) and rotating magnetic field (RMF) [2].

7. Conclusions

1. Commonly performed welding processes usually involve steel structures and are often conducted using the DC arc, thus favouring the occurrence of a detrimental phenomenon, i.e. magnetic blowout.
2. The welding personnel's scope of qualifications should include knowledge concerning the primary principles related to the protection of the welding arc against the adverse effects of magnetic fields.
3. In some cases, the elimination of the magnetic blowout can be achieved by using non-magnetic materials or magnetic screens. If the aforesaid solutions are unfeasible, it is possible to connect the DC power supply source to the appropriate terminals of the element subjected to welding. Another solution involves connecting several additional AC power supply sources to elements being welded or magnetic coils, including elements subjected to welding.
4. Without an additional magnetic field, the welding arc is characterised by a relatively small number of available parameters necessary for controlling the processes of welding, surfacing, hardening, spraying, etc., thus impeding the obtainment of high-quality welded joints, welds, etc. In such a situation, the efficiency of technological processes may also prove insufficient.
5. The above-presented structures of electric connections of arc power sources and elements subjected to welding are important as they are related to frequently performed welding processes.

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