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The Current State of the Art and the Issues of the Drawn Arc Welding of Studs Performed Using a Ceramic Ferrule

Abstract: The authors performed the state-of-art analysis of recent achievements concerned with drawn arc stud welding involving the use of ceramic ferrules. The research focused on surface preparation, technological parameters, process limits and magnetic arc blow. Because of the complexity and correlations of primary electromagnetic phenomena in stud welding processes as well as due to the lack of simple and practically applicable theoretical explanation of their effect on welding results, emphasis was given to demand for industrially applicable simulation tools enabling the forecasting of stud welding results. It is believed that the above-named goal could be achieved using the non-linear regression model of an artificial neural network based on empirical data obtained on a real-time basis from simple process controlling measurement circuits.

Keywords: arc stud welding; shear connectors; ceramic ferrule; drawn arc; magnetic arc blow; weld flash

Introduction

The process of drawn arc stud welding (method EN ISO 4063) [1] is well-established among methods applied industrially when joining structural elements. However, in spite of its multi-annual presence, the process is characterised by phenomena still difficult to describe unequivocally. One of the most problematic issues in industrial practice is magnetic arc blow, significantly and directly affecting the quality of welds. The analysis of the current state of the art justifies a statement according to which the previous achievements in the arc welding of bolts have failed to provide effective remedies in this area.

Essence of the process

The process of arc drawn stud welding involving the use of a ceramic ferrule consists in lifting the stud from above the material, the striking of arc (in the newly formed gap), partly melting surfaces (the above-named arc being preceded by auxiliary arc), and, after lowering the stud, the terminating of arc, pressing the stud into the pool and the solidification of the weld. The above-presented process provides the high quality and repeatability of joint properties and is composed of the following stages [2, 3, 15]:
– placing a connector along with a protective ferrule on the welding gun and placing the

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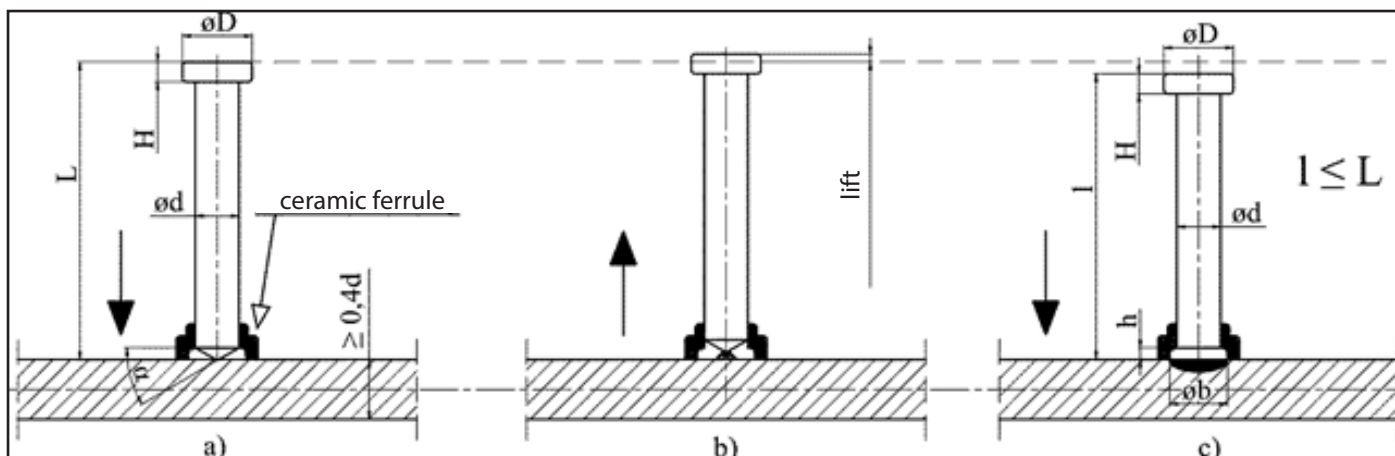
Fig. 1. Schematic diagram presenting stages of drawn arc stud welding involving the use and the lifting of a ceramic ferrule: a) positioning of the connector, b) lifting of the ferrule and arc striking, c) pressing of the stud and the crystallisation of the weld; individual study based on publications [2] and [4]

gun in an appropriate position on the surface of an element (Fig. 1a);

– initiating the process of automatic arc welding, lifting the stud upwards and the striking of high-current electric arc (up to 2500 A) responsible for the local partial melting of materials in the joint areas (Fig. 1b);

– arc termination, pressing the stud against the surface of the element and the fast crystallisation of the weld pool.

The result of the above-presented process is the formation of a joint characterised by uniform penetration on the entire area of the cross-section of the connector. Joints made using drawn arc and a ceramic ferrule are characterised by the fact that the cylindrical surface at the bottom part of the welded stud is surrounded by the metallic weld flash (collar) characterised by a relatively low height and a shape determined by the internal dimensions of the ferrule. (Fig. 1c).

Surface preparation

To ensure the correct course of the arc welding process and to obtain welds representing required quality, the surface of a metallurgical product or of a structural element to be joined with studs should be subjected to cleaning. It is necessary to remove impurities usually formed during production processes, i.e. rust, rolling scale, primer residue, layers of fat,

grease and other substances. It is necessary to obtain a glossy metallic surface at least in the areas containing marks designating the location of welds (to be made) and their direct neighbourhood. The use of high-strength steels (e.g. grade S460) is accompanied by higher risk of hydrogen-induced crack formation. In such cases, because of the hygroscopic properties of impurities, the meticulous removal of the surface layer from base materials is of particular importance. To ensure the obtainment of the required quality of a joint in relation to insufficient surface purity, it may become necessary to reduce the previously assumed value of current by approximately 10%, extend the process duration by approximately 1/10 and increase a step by approximately 0.5 mm [3, 5÷7].

Technological parameters

During the process of drawn arc stud welding involving the use and lift of a ceramic ferrule, the operator can adjust the value of current (Table 1), the exposed length of a stud (Table 2), the time of current flow (Table 3), the step (pitch) of a probe (Table 4) and the damping of the movement during stud immersion (translating into the stud immersion rate).

The recommended speed of stud return during the flow of welding current (i.e. immersion in the liquid metal pool) amounts to 100 mm/s in relation to $\varphi < 16$ mm and 200 mm/s in

relation to ø ≥ 16 mm. Usually, it is recommended to perform welding processes using the relatively low resistance of the return movement of the previously lifted stud so that its return rate could amount to approximately 120 mm/s. In the event of the excessive amount of spatter, distorted flash, undercuts or hissing sounds accompanying the immersion of the stud into the weld pool, it is necessary to readjust the moderator setting. The foregoing results from an increase in damping intensity and, consequently,

a decrease in the return rate of the stud to approximately 60 mm/s. However, the slowing down of the stud immersion rate translates into the extension of actual welding time in relation to the previously adopted value. Heat emitted during the welding process is discharged longer (from materials being joined). If the stud is immersed in the excessively cooled weld pool (the so-called cool welding), the joint is formed improperly [3, 5, 6, 11].

Table 1. Recommended ranges of welding current used when joining studs having various diameters; individual study based on experiments and publications [3, 5÷10]

Stud diameter, mm	Approximate value obtained using a related empirical formula, A	Value recommended by equipment manufacturers, A	Optimum value determined experimentally, A
16	$I \approx 80 \cdot d$ [mm] ≈ 1280	1100 ÷ 1400	1420 ÷ 1570
19	$I \approx 90 \cdot d$ [mm] ≈ 1710	1500 ÷ 1700	1750
22	$I \approx 90 \cdot d$ [mm] ≈ 1980	1850 ÷ 2100	1920 ÷ 2070
25	$I \approx 90 \cdot d$ [mm] ≈ 2250	≥ 2300	2220 ÷ 2350

Table 2. Recommended exposed length of studs having various diameters; individual study based on experiments and publications [3, 5÷10]

Stud diameter, mm	Value recommended by equipment manufacturers, mm	Optimum value determined experimentally, mm
16	3.00 ÷ 3.25	2 ÷ 3
19	3.00 ÷ 3.75	3 ÷ 4
22	4.00	4 ÷ 4.5
25	4.50 ÷ 5.00	5

Table 3. Recommended current flow time when welding studs having various diameters; individual study based on experiments and publications [3, 5÷10]

Stud diameter, mm	Approximate value obtained using a related empirical formula, ms	Value recommended by equipment manufacturers, ms	Optimum value determined experimentally, ms
16	t [s] $\approx 0.04 \cdot d$ [mm] ≈ 0.64 s = 640 ms	550 ÷ 650	550 ÷ 650
19	t [s] $\approx 0.04 \cdot d$ [mm] ≈ 0.76 s = 760 ms	700 ÷ 850	750
22	t [s] $\approx 0.04 \cdot d$ [mm] ≈ 0.88 s = 880 ms	900 ÷ 1050	900 ÷ 950
25	t [s] $\approx 0.04 \cdot d$ [mm] ≈ 1.00 s = 1000 ms	1000 ÷ 1200	1000 ÷ 1150

Table 4. Recommended step (pitch) values when welding studs having various diameters; individual study based on experiments and publications [3, 5÷10]

Stud diameter, mm	Value recommended by equipment manufacturers, mm	Optimum value determined experimentally, mm
16	3.00 ÷ 3.50	2 ÷ 3
19	3.75 ÷ 4.00	3 ÷ 4
22	4.50	4
25	4.50 ÷ 5.50	5

Constraints of drawn arc stud welding

The analysis of reference publications has revealed that scientists have not yet undertaken to investigate how the arrangement of clamps and earth conductors (work leads) of the electric welding circuit affect the quality of welded joints. Similarly, related scientific publications lack information concerning the phenomenon of magnetic arc blow and how the positioning of the welding gun along with its conduits affects the shape of welds. Apart from fragmentary instructions for workshop practitioners published in the form of short brochures containing technical guidance formulated by producers of equipment and studs [12], the above-presented issue seems to be marginalised. Sporadically, it is possible to come across only generally described physical phenomena decisive for the direction of current flow in an electric circuit. Attempts at systematising cause-and-effect relationships between the location of individual elements of the circuit and the final result of the joining process has proved insufficient.

The unquestionable importance of the above-presented issues is confirmed by the fact that they became the object of interest of international standardisation committees in the early 1990s Welding and allied processes" took place on 1st March 1992) [12]. In spite of unflagging interest in arc stud welding, as evidenced by successive issues of the EN ISO 14555 standard [13], the fragments of the standard concerning the above-named correlations leave much to be desired as regards the detail and complexity of the analysis of the problem. The authors only pointed to a few measures preventing the formation of welding imperfections and other undesired results of the joining process [13]. Regrettably, the standard lacks the precise clarification of issues related to the shape of flash and penetration depth. Another drawback often referred to while discussing the content of the standard is its lack of a holistic approach, i.e. presenting individual problematic cases as entirely autonomous [14].

At the same time, there is no doubt that the propagation of electric current during stud welding affects the shape of flash and the weld penetration area. The aforesaid effect is so strong that even the proper adjustment of time-current parameters does not often produce acceptable results. Particularly problematic is the arc welding of large-sized studs, i.e. having diameters ≥ 19 mm and lengths exceeding 150 mm. For instance, during the welding of studs SD1 (22x150) in accordance with EN ISO 13918, in spite of applying parameter adjustments recommended by the manufacturers of the welding power source, the changeable positioning of the welding gun and earth leads resulted in the obtainment of joints characterised by highly varied quality [10].

Issues triggered by magnetic arc blow

There are two primary reasons for the generation of undesired welding arc blow (deflection) [8, 14, 15]:

– thermal arc blow component, related to the strong ionisation of gases in the direct vicinity of welding arc, noticeable in the case of the eccentric position of the stud in relation to the steel holder or the ceramic ferrule.

The foregoing may distort the axiality of electric arc column geometry during the passage of current from the welding gun to the base material;

– magnetic arc blow component, resulting from the combined effect of external magnetic fields, originating from electric conduits, base material and the welding gun. In such a case, welding arc is deflected in the direction opposite to the direction of current flow, usually identical with the route of the electric path characterised by the lowest resistance (Fig. 2).

The one-sided distribution of electric current increases the density of electromagnetic field force lines on the earth clamp side (Fig. 3). This results in the formation of the privileged direction of current flow, deflecting arc in the opposite direction. The direction of deflection defines the area of weld flash characterised by higher volume with the simultaneous reduction or even the lack of weld flash on the other side. Along with an increase in the stud diameter, the above-presented phenomenon increases the risk of porosity formation in flash because of strong whirls of liquid and air in the ceramic ferrule area. In addition, varied melting around the stud circumference usually translates into the greater amount of spatter and the non-uniform contraction of the cooling weld, which, in turn, could result in the lacking perpendicularity of
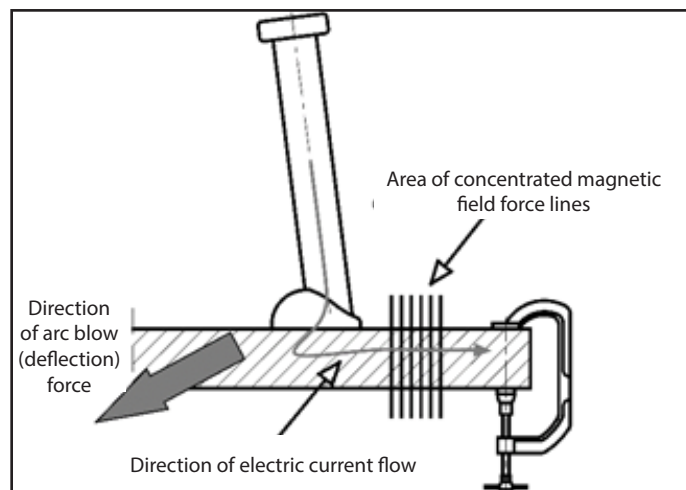

Fig. 2. Schematic diagram presenting the effect of the arrangement of magnetic fields during arc stud welding on the geometry of electric arc; individual study based on publication [8] and [14]

the stud in relation to the base material surface (Fig. 2). For this reason, before the process of arc stud welding it is necessary to visually inspect the technical condition of electric and control conduits of the welding gun as well as that of the earth leads, including terminals. The detection of any damage should preclude the performance of welding works. In addition, the plug of the earth lead should be properly put in the jack (in accordance with the "push and twist" principle), usually located in the front panel of the welding power source. An overly loose connection may disturb the stability of welding arc burning and result in the faster wear of the plug and/or the jack [7÷9, 14].
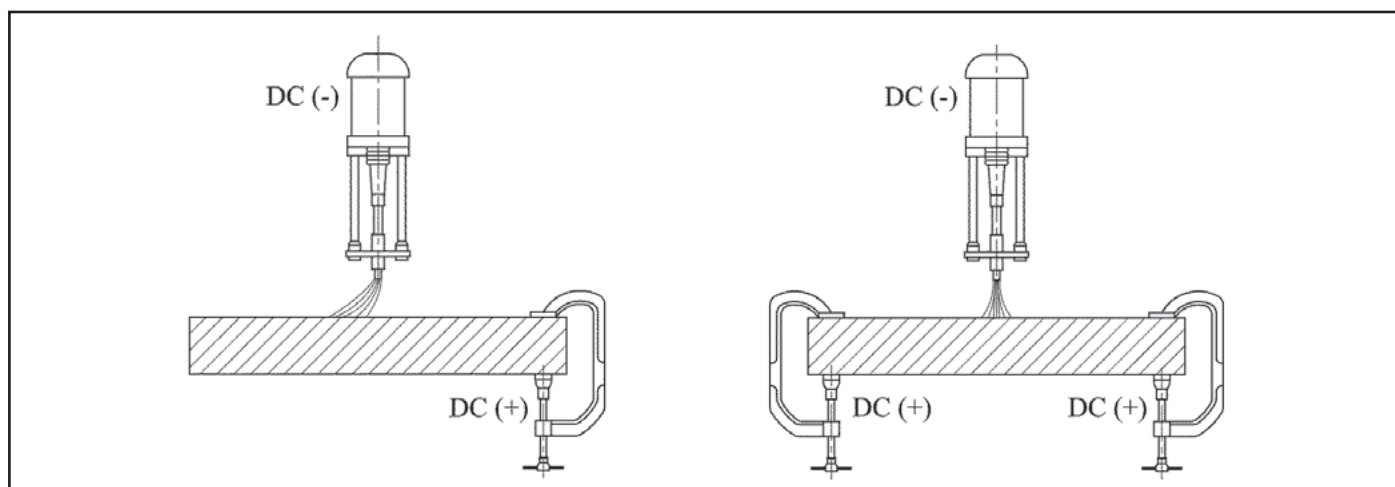

Fig. 3. Pictorial presentation of welding current distribution effect: a) one-sided distribution – easily visible electric arc blow (deflection) in the direction opposite to the privileged direction of electron movement; b) recommended symmetric arrangement of earth clamps of the welding power source aimed to minimise the deflection of electric arc (arc blow) from the axis of the stud being welded; individual study based on publications [13÷15]

It should be noted that the electric leads of the welding gun generate a magnetic field pushing electric arc away from the holder axis (longitudinal axis of the leads) towards outside. The uniformisation of the effect of such a magnetic field on the axiality of electric arc is possible if the welding gun is positioned in the plane of the earth clamps, where the holder along with the supply leads should be positioned at a right angle in relation to the above-named plane (Fig. 3b).

Another issue is the full-length unwinding of the leads and ensuring that the leads are not tangled or twisted as otherwise the force of electromagnetic fields originating in these conductors is significantly intensified as a result of self-induction. The foregoing may disturb arc burning stability or result in the axial deflection of arc. It is recommended that the leads should be arranged in a U-shaped manner or in a large-radius circle or should adopt the shape of an ellipsis fragment. The end of the earth lead with a tong clamp, screw clamp or a tong and screw clamp should be connected directly to the element to be welded, with studs as close to the welding area as possible. It is important that the above-named clamps be carefully twisted to the metallically pure surface. It is also desirable that translational motion should not significantly affect the distance between the weld being made and the earth clamps. In other words, in each case the welding area should remain central between the clamps of earth leads. If need be, the position of the clamps should be corrected as welding works progress [7, 8, 14, 15].

The significant accumulation of ferromagnetic materials on one of the sides of the longitudinal axis of the base material deflects arc towards the material characterised by lower magnetic resistance (Fig. 4a). The prevention of the aforesaid undesired phenomenon involves the one-sided distribution of electric current (Fig. 4b) or the adding of extra ferromagnetic masses on the edge of the surface in the welding area. In the latter case, it is necessary to provide the close magnetic/electric contact of a material being joined (the so-called compensating mass) with the base material. Any air-gaps constitute barriers characterised by higher magnetic resistance and induce the scatter of force lines of magnetic fields. For this reason, it is essential to precisely match metallically pure surfaces. The spatial arrangement of compensating masses in relation to the base material remains irrelevant. In the above-presented case, the central role is played by the quality of contact and the total volume of ferromagnetic materials [7, 8, 15].

Electric arc blow related to the non-uniform distribution of the ferromagnetic material occurs particularly often when welding studs on surfaces of I-section shelves or plate girders. In
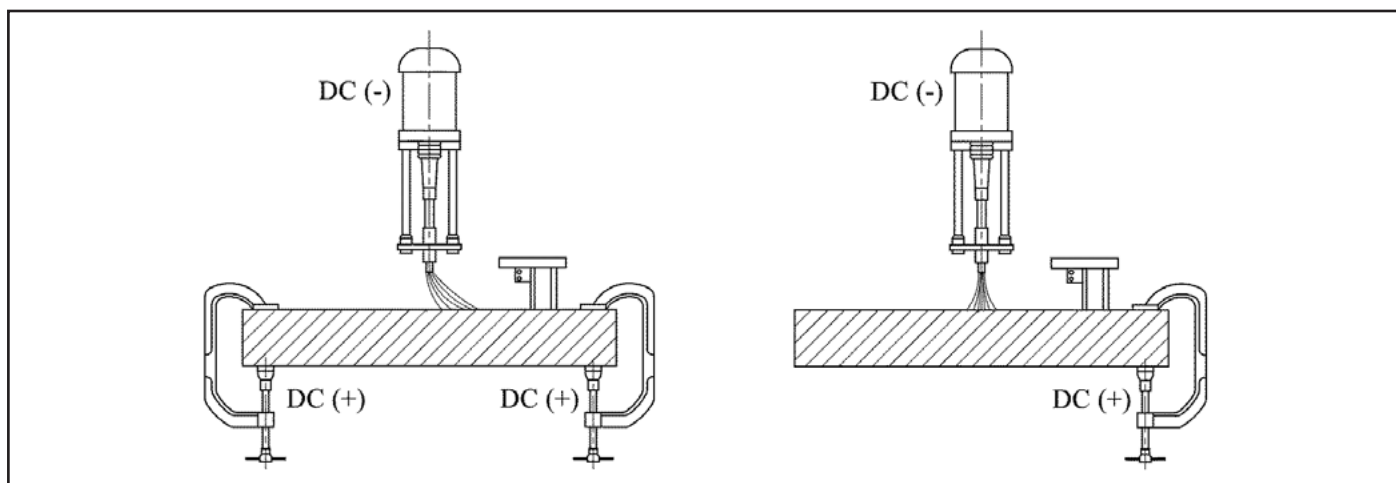

Fig. 4. Schematic presentation of welding arc blow triggered by reduced magnetic resistance: a) towards the greater volume of the ferromagnetic material; b) one-sided flow of electric current suggested as a remedy for the undesirable non-uniform distribution of ferromagnetic masses during arc stud welding; individual study based on publications [13÷15]
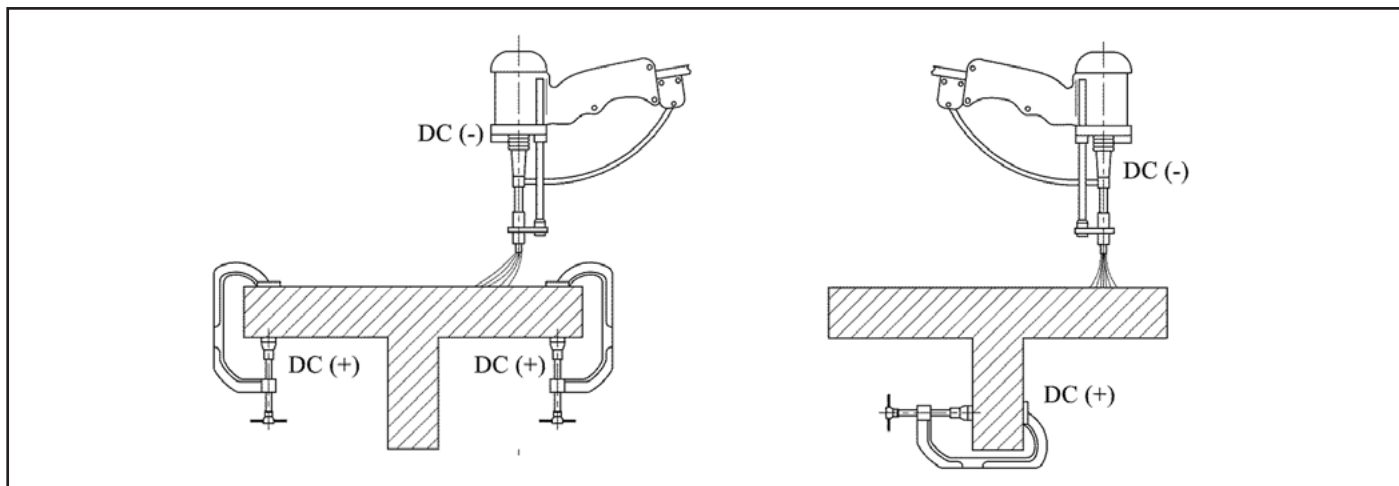
Fig. 5. Schematic presentation of welding arc blow triggered by reduced magnetic resistance and the vicinity of the earth clamp: a) towards the greater volume of the ferromagnetic material; b) one-sided flow of electric current and the appropriate orientation of the welding gun suggested as remedies for the undesirable non-uniform distribution of ferromagnetic masses during arc stud welding: individual study based on publications [13÷15]

such cases, the blow is always directed towards the web (Fig. 5a). To prevent the above-named phenomenon resulting from the effect of the magnetic field generated by the welding gun leads it is necessary to direct the supply leads of the welding gun towards the farther edge of the element. It is also possible to distribute electric energy one-sidedly, i.e. by fixing the earth clamp at the end of the web (Fig. 5b).

Concluding remarks

Reference publications provide information concerning few selected cases of drawn arc stud welding and are limited to between ten and twenty works exclusively concerned with the effect of surface preparation [16÷17] as well as the effect of measurable welding process parameters on the quality of obtained joints [18÷22].

The monitoring of arc stud welding is restricted to the comparison of the final results of the process with a previously assumed desirable result (e.g. the external appearance of welds or, in cases of devices featuring complex data recording modules, mean values of obtained parameters). Frequently, because of a large number of hard-to-associate factors, the above-named monitoring is neglected. The simple principle of adjusting technological variables based on previous experimentation results and manufacturers' recommendations does not

always prove effective in view of the fact that there are two additional significant factors (unmeasurable in production conditions), i.e. the position of clamps and leads of the power circuit and the orientation of the welding gun.

The complexity of many interrelated variables affecting the final result of arc stud welding precludes the development of an easy practically applicable analytical description. Therefore, it seems justified to create an effective simulation tool adjustable to variable technological conditions, enabling the analysis of the extensive range of (sometimes elusive) parameters and the forecasting of joining results in everyday industrial practice. In view of the foregoing, the computed model of artificial neural networks (utilising non-linear regression methods) seems to be capable of meeting the aforesaid challenge. The appropriate training of networks is possible on the basis of data obtained using simple measurement circuits, usually applied in the real-time monitoring and collection of data concerning applied technological parameters. The overview of reference publications demonstrates the possibility of effectively adapting such a simulator for research related to metallurgy and foundry engineering [23÷24]. Unidirectional neural networks only modelling selected aspects of processes without the necessity of developing a detailed theory

explaining the course of analysed phenomena are increasingly often used in welding engineering-related experimentation [25÷26], including arc stud welding [27].

The source of process variability is the interaction of the above-named classifying factors and the analysis of selected features recorded in time. The definition of interaction in the form of a neural network will make it possible to obtain the instruction saying "perform welding" if the quality of a joint in relation to the position of the leads and of that the gun appears acceptable. If the quality of a joint in relation to the arrangement of circuit elements is unacceptable, the neural network will generate instruction saying "do not perform welding". The verification of the effectiveness of the neural network activity will be based on the comparison of final values simulated by the model within the entire range of the variability of both factors with the results of measurements performed using the station.

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