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The challenges of the inverse problems solution in welding technology: a review and a practice

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Abstract. Methods for solving the inverse technological problem, which consists in determining the welding parameters by the desired properties of the welded joint, are discussed. The quality criteria of welds have been developed, which can be used to solve the inverse problems of welding technology. In the simplest case, weld sizes and their ratios may be the quality criteria. The time and space are considered discrete during the modeling thus the equations describing welding process are transcendental equations. The transcendental equations included in the systems colligate welding parameters such as current, arc voltage, travel speed, electrode diameter, its extension, physical properties of welding metal from one hand and quality criteria from another hand. One of the methods of solving the inverse technological problems is the solving of systems of transcendental equations. The mathematical support is discussed and the application of the graphical method for determining the welding parameters is shown.

The possibility of determining the optimal welding parameters using methods of nonlinear programming is shown also. According the method of Lagrange multipliers one have formed the expression in which the most important weld quality criteria are used as an object function. Other quality criteria were accepted as constraints. Solving the expression obtained in the space of restrictions on welding parameters, welding parameters are obtained that deliver the local conditional optimum of the subject function.

Keywords: Mathematical model, reverse problem, arc welding

1. Introduction

Arc welding is widely used in the industry of metal constructions. The certified welders work using welding machines also the automated devices and robots are exploited in the welding industry. By means of owns experience and trial-and-error approach, a welder determines the welding parameters needed to achieve the sound welds. The method of determining of welding parameters using desire quality criteria of welding joints we will name an inverse technology problem. This very difficult mathematical task cannot be solved in a mind. Therefore, often non-optimal welding parameters are exploiting in welding technology and many weld imperfections are formed.

For that reason, the great need of the mathematical relationships between quality criteria of welds and welding parameters exists and the developing of welding procedures is an expensive part of the quality assurance system for any fabricator. Usually, in the form of a sheet document, the Welding
Procedure Specification (WPS) is the final link in the chain of documents required to demonstrate welding process control. It comprises all the relevant information required by a welder or a robotics engineer to produce sound welds. The WPS gives an allowable range of welding parameters that might be used. Welding current $I$, arc voltage $U$, travel speed $V$, preheat temperature $T_0$, tungsten or wire diameter $d$ and its extension are included in the WPS for arc welding.

Because weld quality is multi-faceted, so there are many quality criteria of welding. Each such criterion estimates only one side of weld quality. There are the criteria that establish the geometric quality, and imperfections or mechanical quality of a weld and so on. Other criteria of weld quality, for example, describe the absence of imperfections, such as undercuts, cold cracking, and etcetera. Quality criteria of welding joint in the simplest case include the geometric sizes of weld. The mechanical properties of a weld and the HAZ are also the quality criteria in welding of hardening steels. The determination the effects of welding parameters on quality criteria is treated as the solving of a direct technology problem. This problem may be solved by various methods such as theoretical (theory of heat flow) [1], statistical [2],[3], using artificial neural networks [4], [5], fuzzy logic [6], and their combinations [7].

The determination the optimal welding parameters using desired quality criteria is treated as the solving of an inverse technology problem. Nowadays it is known some solving methods of this problem but some of them do not allow one to calculate quickly the optimal welding parameters, others are too complicated for everyday use by welders and engineers.

Numerical simulation of welding process has made considerable progress. Today many manuscripts describing numerical models of various kinds of welding were published. However, as well as an experimental method, the numerical simulation requires considerable time to find welding parameters. Both methods allow determining "allowable" range of welding parameters after long time experiments using “try-and-error method.” There is no guaranty that the range of welding parameters searched by such manner is optimal in terms of mathematics, quality, and productivity.

The problem of this article is to determine quality criteria, to develop the mathematical relationships between quality criteria and welding parameters, an objective function, and the methods that are suitable for solving technology inverse problems of arc welding.

Determination of optimal welding parameters in the case of multiple criteria is very difficult for mathematical solutions. Some significant manuscripts devoted this subject is discussed below. A detailed review of known methods of solving the inverse problem is given in [1].

2. The mathematical apparatus of the calculation methods of the inverse problems solving
To solve this problem in GMAW, it is first of all necessary to determine the quality criteria and the equations connecting them with the parameters of the welding regime such as welding current, arc voltage, travel speed, electrode diameter and its stickout distance.

2.1. Quality criteria
The term “partial criteria of quality” (PCQ) and complex criteria of quality (CCQ) have been introduced in [8]. For example, the PCQ of a single square-groove weld using the penetration depth $h$ was written in the form

$$\Delta h = h_{d} - (h \pm \delta h)$$  \hspace{1cm} (1)$$

where $h_{d}$ is the desired depth of penetration, $h$ is the calculated value of depth of penetration, $\delta h$ - is the confidence interval of the estimated value $h$ for a given confidence probability.

In accordance with (1), the burn-through is reflected by negative values $\Delta h$, the lack of penetration is positive $\Delta h$, and the sound weld will have $\Delta h = 0$. Similarly, other weld dimensions can be written as PCQ. Similarly, other seam dimensions, such as the weld width and the reinforcement, can be written as PQC.
Complex criteria of quality were formed as the ratios of the weld dimensions taken as PCQ. As is shown in [9], these ratios are associated with such important flaws of welds as hot cracks, lack of root penetration and stress concentration.

Thus, the next quality indicator - the “ratio width to depth” (ratio E to h) is accepted as the CCQ and is written as inequality

$$\psi_{M_{\min}} \leq \psi_{M} \leq \psi_{M_{\max}} \quad (2)$$

where \(\psi_{M}\) is width – depth ratio, \(\psi_{M_{\min}}\) and \(\psi_{M_{\max}}\) are defined for groups of steels and welded joints according to literature data [10]. This CCQ determines conditions for their formation of solidification cracks.

The CCQ “the ratio width to reinforcement” (ratio E to g) determining stress value at toe was introduced as

$$\psi_{R_{\min}} \leq \psi_{R} \leq \psi_{R_{\max}} \quad (3)$$

where \(\psi_{g}\) is the ratio of weld width to height of reinforcement, \(\psi_{R_{\min}}\) , \(\psi_{R_{\max}}\) are decided as for concrete joint taking into account the calculations and data of Nikolaev [11] and considering variant of GTAW. In conditions of carbon dioxide welding the range \(6 \leq \psi_{R} \leq 10\) is acceptable.

To avoid incomplete joint penetration of double-groove weld its quality is additionally determined by the overlap of penetrations. For a guaranteed complete root penetration, it is sufficient that

$$h_1 + h_2 = s + k_O \quad (4)$$

where \(s\) is the double- welded joint thickness, the \(h_1, h_2\) is the joint penetration from the first and the back side of a joint, respectively, \(k_O\) is the overlap of joint penetrations. From (4) we have obtained the formula for calculating the quality indicator of double-groove welds

$$\psi_{O} = \frac{h_1}{s} + \frac{h_2}{s} = 1 + \frac{k_O}{s}. \quad (5)$$

Assuming that \(k_O = \frac{s}{3}\) we have the minimum value of \(\psi_{O_{\min}} = 1.3\). Taking the maximum value \(k_O = \frac{2}{3}s\), we obtained the maximum value of \(\psi_{O_{\max}} = 1.6\). Finally, the CCQ “overlap” has the form

$$\psi_{O_{\min}} \leq \psi_{O} \leq \psi_{O_{\max}}. \quad (6)$$

To find the solution of inverse technology problems one may put into execution by some methods. Some of them are described below.

2.2. Equations connected quality criteria and welding parameters

Equations connected quality criteria and welding parameters are the transcendental equations obtained experimentally using the similarity criteria. For example, the depth of penetration when welding of butt joints in carbon dioxide from mild steel can be described by the equation

$$h = e^{-1.473} \cdot d^{0.33} \left( \frac{\eta U}{(T - T_p)} \right)^{0.67} \left( \frac{b}{d} \right)^{0.335} \cdot V^{-0.665}. \quad (7)$$

where \(a=0.084\ cm^2/s\) is thermal diffusivity, \(\lambda=0.42\ W/(cm\cdot K)\) is thermal conductivity adopted for \(T=20...600^\circ C\), \(T=1330^\circ C\) is the melting temperature of mild steel, \(\eta=0.8\) is the affectivity of a welding heat source in GMAW, \(b\) is a root opening, \(T_p\) is the preheat temperature.

Dispersion of welding parameters is calculated by the common formula of "law of propagation of error" [12]. In a study of GMAW the dispersion of the penetration depth described by Equation (7) may be calculated as

$$s^2(h) = \left( \frac{\partial h}{\partial I} \right)^2 s^2(I) + \left( \frac{\partial h}{\partial V} \right)^2 s^2(V) + \left( \frac{\partial h}{\partial U} \right)^2 s^2(U) \quad (8)$$
where \( s^2(h), s^2(I), s^2(V), s^2(U) \) is the variance of penetration depth, the variance of welding current, of welding speed and arc voltage correspondingly.

To estimate the variance of each welding parameter current, travel speed and arc voltage the “three sigma rule” [13] was used to calculate. A standard deviation each of they were determined considering those maximum deviations of I, U and V known from the practice of welding. To determine the confidence intervals of calculated value of weld sizes the next expression was used [13] for example for \( h \)

\[
\delta h = \left[ h - t_{\beta} \left( s^2(h) \right)^{1/2}; h + t_{\beta} \left( s^2(h) \right)^{1/2} \right]
\]

(9)

where \( t_\beta=3, t_{1.96}=1.96 \) when probability is equal 99.73% and 95% respectively.

3. A graphical method
This method assumes that the mathematical dependencies between the PCQ and the welding parameters are established (known). However, the mathematical method of finding a solution is not applied. To determine the area of optimum process parameters \( G_{optim} \) satisfying all the PCQ for any weld it is necessary to perform the operation of intersection of the sets obtained for each PCQ

\[
G_i \cap G_{i1} \cap G_{i2} = G_{optim},
\]

(10)

where \( G_i (i=1...n) \) is the area of \( i \)-th PCQ. In the simplest case, this method involves graphically plotting the areas of all criteria on a single graph.

This approach was applied by the Hsu [14] to determine the parameters of the stud welding and Babkin [8] has employed it for the GMA welding of square-butt joints.

Having mathematical dependencies between the PCQ and the welding parameters, it is possible to calculate the CCQ criteria that are their relations. And it is possible to use multiple CCQ to assess weld quality, for example \( \psi_M, \psi_R \) and \( \psi_O \). Figure 1 shows an example of using this method to determine the welding parameters of a double butt-square joint \( s=4 \text{mm} \) and \( b=1 \text{mm}, d=1.2 \text{mm} \) in carbon dioxide. The CCQs \( \psi_O \) “overlap” and \( \psi_M \) “ratio width to depth” has been calculated. Accordance with the above reasoning the sound welds can be formed in region where \( 1 \leq \psi_M \leq 5 \) [10] and \( 1.3 \leq \psi_O \leq 1.6 \). The white dashed lines indicate the calculated using \( CCQ-1.96\left( s^2(CCQ) \right)^{1/2} \) the high boarder of confidence interval, the black solid lines indicate the calculated using \( CCQ+1.96\left( s^2(CCQ) \right)^{1/2} \) the low confidence interval at \( t_{1.96}=1.96 \).

The experimental verification of the optimal parameters of the regime obtained using of the developed methods showed a good coincidence of the calculated CCQ with the experimental values. The white circle marks in figure 1 the welding parameters on which the welding of this joint was performed. The control joint welded in \( I=130 \text{A}, U=22 \text{V}, V=0.81 \text{ cm/s} \) has the following sizes \( h=2.55\pm 0.15, E=6.43\pm 0.18, g=1.25\pm 0.12, \psi_M = 2.47\pm 0.09, \psi_R = 5.34\pm 0.63 \). It is established that the sizes and quality criteria of the obtained weld are very close to those desired.
4. The system of transcendental equations

The simplest nonexperimental method of welding parameters determination is obvious and it is that to solve mathematically the system of equations. However, there are very little investigations, which have solved an inverse problem such manner. Apparently, this approach was first applied by Krivosheya [15] for SAW and Savage et al. [2] for GTAW, then Babkin and Krivosheya [16]-[18] have practiced it for welding in carbon dioxide. The equations included in a system must describe the relations between sought-for welding parameters and desired sizes of a weld or the HAZ. The equations may be linear or curvilinear. They can be obtained either experimentally or using the theory of heat transfer. If the equations are not linear, then for the sake of simplicity of the calculation algorithm they are linearized by taking logarithms.

Savage et al. [2] have suggested using the regression equations derived by them to calculate the welding parameters of GTAW. Some regression models expressing weld-puddle-shape dimensions as a function of welding parameters were developed. This model was capable only of calculating the welding current and velocity. More importantly, the authors have mentioned since the prediction of velocity is still inaccurate and therefore the model can only be used in conjunction with experimental trials. Later, Kim et al [19] applied this method to calculate the parameters of the GMA welding such as $I$, $U$, $V$ by solving the system of three experimentally obtained regression equations connecting bead dimensions and welding parameters. However, all the above mentioned works offer a method of calculating welding parameters of bead-on-plate, i.e. they do not take into account the effect of root spacing and bevel groove on the value of PCQ for butt joint. There are no the works concerning welding parameters calculation of corner, T-joints or lap joints.

In manuscripts written by Babkin and Krivosheya [16]-[18], the algorithm for calculation of the welding parameters was elaborated, in which the systems consisted of 4, 3, and 2 equations were solved consistently. These systems include the equations described the melting of base metal like as Equation (7) and melting of filler metal [20].

5. The using of Lagrangian expression

The parametric conditional optimization is relevant in production conditions, both in terms of the quality of a weld and in terms of the economic parameters of a welding process. If one applies as objective function an equation that connects the PCQ and optimization parameters $I$, $U$, $V$, $d$ similar to (7), then it is possible to practice the classical methods of mathematical analysis to find the extremum of a function if the equations connecting optimization parameters and PCQ are continuous and differentiable. As well, in the practice of welding, the constraints in the form of equalities or inequalities are imposed on the optimization parameters. Such parameter values constraints,
intermediate values constraints, and relation constraints significantly reduce the size of the region in which the optimum is searched. Thus, the optimization problem belongs to the class of constrained one.

As an example, here let’s consider the task of minimizing the welding time of a multiple-pass joint in GMAW provided that the desired penetration of the layers and the cooling rate of each layer will be provided. It is required to minimize the welding time of single-bevel-groove weld while ensuring a desired penetration depth of the previous layer \( h = 3 \text{ mm} \) and the cooling rate \( \omega = 15 \text{ deg/s} \). A single-bevel-groove weld has a length \( L \), a bevel angle, and the deposit area of joint \( F \), which is filled with \( N \) layers. The welding current \( I \), the arc voltage \( U \), the welding speed \( V \), the electrode diameter \( d \) are assumed to be constant throughout the entire welding process and are not changed when the \( i \)-th layer is executed.

The objective function has the form [20]

\[
N_t = \frac{F \cdot \gamma \cdot L}{a_m I} \rightarrow \min
\]  

where the \( N \) is the number of weld passes, the \( t \) is welding time of \( i \)-th weld pass, \( a_m \) is the coefficient of wire melting [20], \( L \) is a joint length, \( F \) is the cross section deposit area of a joint, \( \gamma \) is specific weight.

The constraint as the penetration depth \( h \) was obtained for welding in carbon dioxide experimentally in the form (7).

The cooling rate of HAZ metal of butt joints can be calculated using the following relationship[1]

\[
\omega = \left( \frac{V \cdot \delta}{2 \pi c_v} \left( \frac{V \cdot \delta}{\eta \cdot I \cdot U} \right)^2 \cdot (T_m - T_p) \right)
\]  

where \( c_v \) is the volume thermal capacity, \( \delta \) is the joint thickness, \( T_m \) is the temperature of minimum stability of austenite.

The Lagrange expression formed from these equations was solved in Mathcad software. First of all, using the system of equations the welding parameters of root weld was calculated without taking into account the cooling rate. Further, the deposit area of the root pass \( F_R = 6\text{mm}^2 \) was calculated by the formula [20]. The difference between the deposit area of the joint \( F = 27\text{mm}^2 \) calculated as a function of bevel angle 20 deg, depth of bevel 8.5 mm, root opening 0.1 mm and the value of \( F_R \) was adopted as \( F \) in (11). Having adopted \( F = 21\text{mm}^2 \), \( L = 2\text{m} \), \( d = 1.2\text{mm} \), and \( L_e = 15\text{mm} \), \( T_p = 20^\circ \text{C} \), the thermophysical properties of the steel the following optimum welding parameters of intermediate weld bead were calculated: number of weld passes \( N = 1 \), \( I = 194 \), \( V = 17.18 \text{ m/h (0.47 cm/s)} \), \( U = 25.6 \text{V} \).

The calculated value of the Lagrange expression is 0.123. Obtained solution is marked by the white point on the graph (in figure 2) which shows the surface of the Lagrange expression with calculated Lagrange multiplier when searching for the minimum of the above function (22). A mathematical check performed using Hessian matrix showed that the solution delivers the minimum of the Lagrange expression.

6. Conclusions
An extremely demanded task of welding production is the calculation of the optimal welding parameters using the desired dimensions of welds as input data. Such problems are called inverse problems.

Examples of application of several methods for solving inverse problems of gas melting arc welding technology are given. Their mathematical support includes the quality criteria of welds, the mathematical equations connected the lasts and the welding parameters of the regime. It is possible to use the described equations for graphical determination of the welding parameters, for the compilation of systems of equations, and for the formulation of the Lagrange equation. The described techniques allow to quickly and accurately calculate the parameters of the regime, providing the desired weld dimensions.
Figure 2. Lagrange expression views of the calculated problem in Mathcad software. (a) 3-D plot. (b) Contour plot.

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