Optimization of GMA welding parameters using the grasshopper optimization algorithm

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This paper presents the method for choosing optimal parameters for GMA welding of P355GH low-carbon steel plates. The welding parameters such as seam overhang coefficient, degree of mixing, number of passes and welding current were obtained using the grasshopper optimization algorithm (GOA). Optimal parameters were obtained to yield minimum welding costs while considering technological constraints such as maximum permissible cooling rate and maximum permissible hardness of the heat affected zone (HAZ).

Keywords: Optimization, GMA welding, Grasshopper optimization algorithm

1. INTRODUCTION

In the welding process, the costs, cycle time and quality of the welded joint are highly dependent on the welding parameters such as seam overhang coefficient, seam shape coefficient, degree of mixing, number of passes, welding speed, welding current and voltage. Determination of optimal welding parameters, with regard to different technological constraints, is important task in the process of designing the welding technology.

The main objective of this study is to optimize the butt joint welding costs, which consists of the two partial costs discussed here. Those costs are material costs made up of filler material costs and consumable material (protective atmosphere) costs, and energy costs (electric energy). The optimum parameters: seam overhang coefficient, degree of mixing, number of passes and welding current are found by grasshopper optimization algorithm (GOA) which is a recently developed metaheuristic algorithm. An illustrative example is used to demonstrate the effectiveness of the GOA in process of choosing the optimal welding parameters.

2. GMA WELDING COSTS

2.1. Structure of the GMA welding costs

In [1] are given general structure of the welding costs for different types of welding processes. Based on that structure, it is possible to derive a cost structure suitable for a specific welding process. On the Figure 1 are given costs structure for GMA welding process. In this paper are considered only material costs, T_M and energy costs, T_E, specifically, filler material costs, T_{DM}, protective atmosphere costs, T_{ZA}, and electric energy costs, T_{ES}. Other costs are not taken into account because they are generally less independent of the welding parameters.

2.2. Mathematical formulation of the GMA welding costs

In the following section are given mathematical formulations of costs.

2.2.1. Filler material costs, T_{DM} RSD

These costs can be calculated using the following

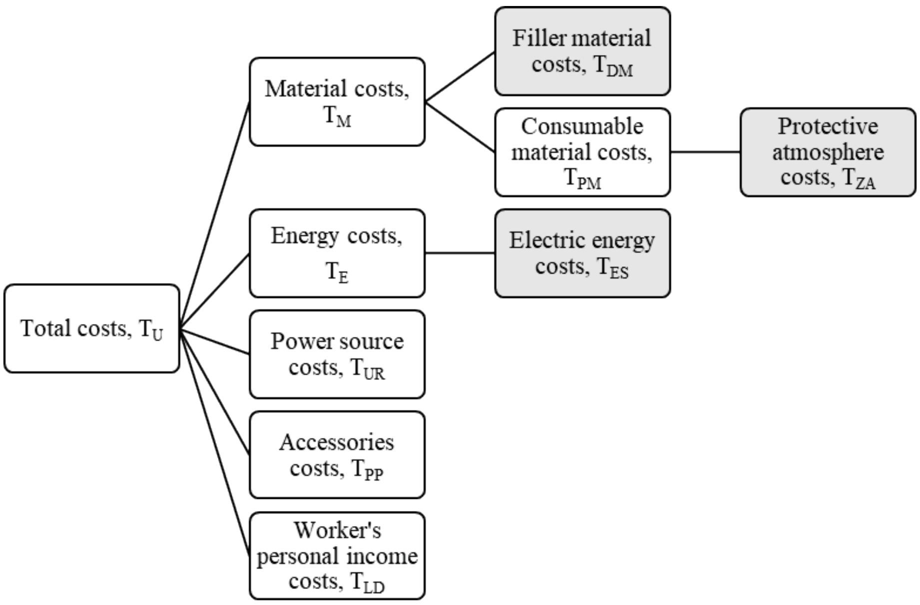

Figure 1: GMA welding costs structure [1]

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equation:

$$T_{DM} = S \cdot V_z \cdot t_z \cdot \rho_e \cdot \eta_e \cdot C_{DM} \quad (1)$$

where:

S m^2, V_z m/min, t_z min, ρ_e kg/m^3, η_e, C_{DM} RSD/kg are cross-sectional area of the groove (Figure 2), welding speed, welding time of one pass, density of filler material, specific productivity of filler material and price of the filler material, respectively. [1]

Equations for variable parameters are listed below.

$$S = c \cdot \delta + (\delta - h)^2 \cdot \mathrm{tg}\frac{\varphi}{2} \quad (2)$$

$$V_z = \frac{6 \cdot 10^{-2} \cdot m_D}{\frac{S_š}{i} \cdot \rho_e} \quad (3)$$

$$t_z = \frac{6 \cdot 10^4 \cdot \frac{S_š}{i} \cdot \rho_e \cdot l_š}{I_z \cdot K_t} \quad (4)$$

It is important to note that an equal cross-sectional area of the weld in each pass is adopted here. [1,2]

Next parameters must be calculated, using following equations:

$$m_D = 2.5 \cdot \sqrt{\frac{2 \cdot S_š}{i} \cdot \rho_e} \quad (5)$$

$$S_š = \frac{S + 0.75 \cdot \frac{e_1}{\zeta} \cdot e_1 + 0.75 \cdot \frac{e_2}{\zeta} \cdot e_2}{1 - \gamma} \quad (6)$$

$$K_t = 0.0001 \cdot I_z^2 - 0.0279 \cdot I_z + 15.5643 \quad (7)$$

Here, m_D g/s, $S_š$ m^2, K_t g/(A·h), are deposit mass, cross-sectional area of the seam and melting constant, respectively. [1] It is worth noting that the equation for melting constant was obtained by interpolating the data given in [2].

Parameters e_1 m, e_2 m are the width of the seam on the face side and on reverse side of the face, respectively.

$$e_1 = 2 \cdot (\delta - h) \cdot \mathrm{tg}\frac{\varphi}{2} + c + d_1 \quad (8)$$

$$e_2 = c + d_2 \quad (9)$$

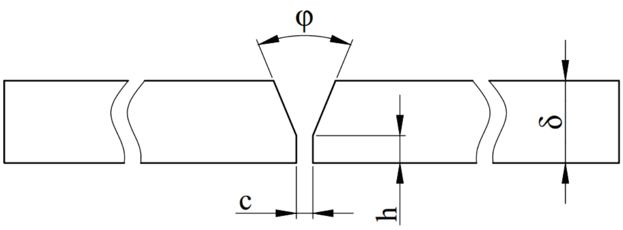

Figure 2: Dimensions of the Y groove

2.2.2. Protective atmosphere costs, T_{ZA} RSD

These costs can be calculated using following equation:

$$T_{ZA} = Q_a \cdot C_a \cdot (t_z \cdot i + t_{pz}) \cdot \frac{1}{\eta_e \cdot \varepsilon} \quad (10)$$

Where t_{pz} min and ε are preparatory-final time and intermittency. They can be calculated using following equations: [1]

$$t_{pz} = k_{pz} \cdot (t_z \cdot i + t_p) \quad (11)$$

$$\varepsilon = \frac{t_z \cdot i}{t_z \cdot i + t_{pz}} \quad (12)$$

2.2.3. Electric energy costs, T_{ES} RSD

These costs can be calculated using following equation:

$$T_{ES} = S_š \cdot V_z \cdot t_z \cdot \rho_e \cdot C_s \cdot \left[\frac{U_z \cdot I_z}{1000 \cdot \eta_s} \cdot \varepsilon + P_0 \cdot (1 - \varepsilon)\right] \cdot \frac{1}{60 \cdot PR_D \cdot \varepsilon} \quad (13)$$

Where PR_D kg/min is productivity by amount of deposited material, and is calculated by following equation: [1]

$$PR_D = S_š \cdot V_z \cdot \rho_e \quad (14)$$

2.2.4. Total costs, T_U RSD

Total costs represent the sum of partial costs and they are also the objective function. [1]

$$T_U = T_{DM} + T_{ZA} + T_{ES} \quad (15)$$

3. CONSTRAINTS

Welding is a complex process where the welded joint has to meet various requirements in terms of quality and mechanical properties.

Here, P355GH low-carbon steel is chosen for the material of the welded joint parts.

The objective function (15) is subjected to four technological constraints, which are explained in the following section.

3.1. Constraint regarding the maximum permissible cooling rate

Based on the continuous cooling transformation diagram (CCT) for steel, it is possible to determine which is critical or the maximum cooling rate, at which undesirable structures in the heat affected zone (HAZ) of the steel, especially martensite, will not form. From the CCT diagram for P355GH steel given in [3], we can see that the maximum permissible cooling rate is 50 °C/s.

It is possible to make relationship between the cooling rate v_h °C/s and the cooling time in the temperature interval from $800 \div 500$ °C, $t_{8/5}$ s, from where it is possible to determine the critical or minimum allowed cooling time in that interval, i.e.:

$$t_{8/5} \geq \frac{800 - 500}{v_h} \geq \frac{300}{50} \geq 6 \text{ s} \quad (16)$$

From the cooling time equation [3]:

$$t_{8/5} = \frac{k \cdot q_l^n}{\beta \cdot (T_{sr} - T_0)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \mathrm{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]} \quad (17)$$

it is now possible to get the line energy q_l J/cm :

$$q_l \geq \sqrt[n]{\frac{t_{8/5} \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \geq \sqrt[n]{\frac{6 \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \quad (18)$$

After substituting above inequality into the line energy equation [3]:

$$q_l = 60 \cdot \frac{U_z \cdot I_z}{v_z} \quad (19)$$

we get the following inequality:

$$U_z \cdot I_z \geq \frac{v_z \cdot \sqrt[n]{\frac{6 \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}}}{6 \cdot 10^{-1}} \quad (20)$$

First constraint is:

$$U_z \cdot I_z - \frac{v_z \cdot K_1}{6 \cdot 10^{-1}} \geq 0 \quad (21)$$

Where:

$$K_1 = \sqrt[n]{\frac{6 \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \quad (22)$$

After expressing the voltage over the welding current [3], the constraint finally becomes:

$$\left(14 + 0.05 \cdot I_z\right) \cdot I_z - \frac{v_z \cdot K_1}{6 \cdot 10^{-1}} \geq 0 \quad (23)$$

3.2. Constraint regarding the maximum permissible hardness in the HAZ

The hardness value in the HAZ is used as one of the parameters of the weldability of steel. Maximum permissible hardness is related to the amount of diffused hydrogen.

Based on the recommended hydrogen scale for the GMA welding (D), it is possible to determine the content of diffused hydrogen per 100 g of weld metal ($1 \div 5$) and maximum permissible hardness in the HAZ ($\text{HV}_{\text{max}} = 450$ HV), as explained in [3].

Equation for the maximum hardness is as follows:

$$\text{HV}_{\text{max}} = \frac{\text{H}_\text{M} + \text{H}_\text{B}}{2} - \frac{\text{H}_\text{M} - \text{H}_\text{B}}{2.2} \cdot \text{arctg}\left(\text{X}\right) \quad (24)$$

Where, H_M HV, H_B HV are hardness of martensite phase and bainite phase, respectively. X is parameter which can be calculated using following equation:

$$\text{X} = 4 \cdot \frac{\log\left(t_{8/5} / t_M\right)}{\log\left(t_B / t_M\right)} - 2 \quad (25)$$

Here, t_M s, t_B s are indices of ease of formation of martensitic, and bainite phases, respectively. The equations for these indices are given below.

$$t_M = \exp(10.6 \cdot \text{CE}_\text{I} - 4.8) \quad (26)$$

$$t_B = \exp(6.2 \cdot \text{CE}_{\text{III}} + 0.74) \quad (27)$$

Where parameters CE_I %, CE_{III} % represents the carbon equivalent. [3]

The hardness H_M and H_B can be calculated as follows:

$$\text{H}_\text{M} = 884 \cdot \text{C} \cdot \left(1 - 0.3 \cdot \text{C}^2\right) + 297 \quad (28)$$

$$\text{H}_\text{B} = 145 + 130 \cdot \text{tgh}\left(2.65 \cdot \text{CE}_{\text{II}} - 0.69\right) \quad (29)$$

Where CE_{II} % is carbon equivalent.

The equations for the carbon equivalent are given below. [3]

$$\text{CE}_\text{I} = \text{C}_\text{p} + \frac{\text{Si}}{24} + \frac{\text{Mn}}{6} + \frac{\text{Cu}}{15} + \frac{\text{Ni}}{12} + \frac{\text{C}_\text{r} \cdot \left(1 - 0.16 \cdot \sqrt{\text{Cr}}\right)}{8} + \frac{\text{Mo}}{4} + \Delta\text{H} \quad (30)$$

$$\text{CE}_{\text{II}} = \text{C}_\text{p} + \frac{\text{Si}}{24} + \frac{\text{Mn}}{5} + \frac{\text{Cu}}{10} + \frac{\text{Ni}}{18} + \frac{\text{C}_\text{r}}{5} + \frac{\text{Mo}}{2.5} + \frac{\text{V}}{5} + \frac{\text{Nb}}{3} \quad (31)$$

$$\text{CE}_{\text{III}} = \text{C}_\text{p} + \frac{\text{Mn}}{3.6} + \frac{\text{Cu}}{20} + \frac{\text{Ni}}{9} + \frac{\text{C}_\text{r}}{5} + \frac{\text{Mo}}{4} \quad (32)$$

Based on the constraint $\text{HV}_{\text{max}} \leq 450$ HV and (24) we have the following:

$$\text{X} \geq \text{tg}\left(\frac{1.1 \cdot \left(\text{H}_\text{M} + \text{H}_\text{B} - 900\right)}{\text{H}_\text{M} - \text{H}_\text{B}}\right) \quad (33)$$

After substituting the inequality given above in (25) we have:

$$t_{8/5} \geq t_M \cdot 10^\wedge\left(\frac{\log\left(t_B / t_M\right) \cdot \left(T + 2\right)}{4}\right) \quad (34)$$

Where:

$$T = \text{tg}\left(\frac{1.1 \cdot \left(\text{H}_\text{M} + \text{H}_\text{B} - 900\right)}{\text{H}_\text{M} - \text{H}_\text{B}}\right) \quad (35)$$

Using (17) it is now possible to get the line energy:

$$q_l \geq \sqrt[n]{\frac{t_{8/5} \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \geq \sqrt[n]{\frac{E \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \quad (36)$$

Where:

$$E = t_M \cdot 10^\wedge\left(\frac{\log\left(t_B / t_M\right) \cdot \left(T + 2\right)}{4}\right) \quad (37)$$

After substituting q_l into (19), we get the following inequality:

$$U_z \cdot I_z \geq \frac{v_z \cdot \sqrt[n]{\frac{E \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}}}{6 \cdot 10^{-1}} \quad (38)$$

Second constraint is:

$$U_z \cdot I_z - \frac{v_z \cdot K_2}{6 \cdot 10^{-1}} \geq 0 \quad (39)$$

Where:

$$K_2 = \sqrt[n]{\frac{E \cdot \beta \cdot \left(T_{sr} - T_0\right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot \text{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}{k}} \quad (40)$$

After expressing the voltage over the welding current as in (23), the constraint finally becomes:

$$\left(14 + 0.05 \cdot I_z\right) \cdot I_z - \frac{v_z \cdot K_2}{6 \cdot 10^{-1}} \geq 0 \quad (41)$$

3.3. Constraints regarding the recommended welding voltage values

Taking into account the recommended welding voltage values ($U_z = 22 \div 35$ V) given in [1], and the above-mentioned dependence between welding voltage and current, we have the following:

$$U_z = 14 + 0.05 \cdot I_z \geq 22 \text{ V} \quad (42)$$

$$U_z = 14 + 0.05 \cdot I_z \leq 35 \text{ V} \quad (43)$$

The third and fourth constraints are:

$$8 - 0.05 \cdot I_z \leq 0 \quad (44)$$

$$0.05 \cdot I_z - 21 \leq 0 \quad (45)$$

Furthermore, constraints are associated with the domain of optimization variables [1,2], as follows:

$$\begin{gathered} 7 \leq \zeta \leq 10 \\ 0.1 \leq \gamma \leq 0.6 \\ 3 \leq i \leq 5 \\ 150 \leq I_z \leq 450 \end{gathered} \quad (46)$$

4. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

According to the mathematical modelling described above, the problem of GMA welding costs minimization is as follows:

Minimise $T_U(\mathbf{x}) = T_{DM}(\mathbf{x}) + T_{ZA}(\mathbf{x}) + T_{ES}(\mathbf{x})$

subject to

$$\begin{gathered} g_1(\mathbf{x}) = \frac{v_z(\mathbf{x}) \cdot K_1(\mathbf{x})}{6 \cdot 10^{-1}} - \left(14 + 0.05 \cdot x(4)\right) \cdot x(4) \leq 0 \\ g_2(\mathbf{x}) = \frac{v_z(\mathbf{x}) \cdot K_2(\mathbf{x})}{6 \cdot 10^{-1}} - \left(14 + 0.05 \cdot x(4)\right) \cdot x(4) \leq 0 \\ g_3(\mathbf{x}) = 8 - 0.05 \cdot x(4) \leq 0 \\ g_4(\mathbf{x}) = 0.05 \cdot x(4) - 21 \leq 0 \\ \zeta_{\min} \leq \zeta \leq \zeta_{\max} \quad \left(\zeta = x(1)\right) \\ \gamma_{\min} \leq \gamma \leq \gamma_{\max} \quad \left(\gamma = x(2)\right) \\ i_{\min} \leq i \leq i_{\max} \quad \left(i = x(3)\right) \\ I_{z\min} \leq I_z \leq I_{z\max} \quad \left(I_z = x(4)\right) \end{gathered} \quad (47)$$

5. GRASSHOPPER OPTIMIZATION ALGORITHM

The grasshopper optimization algorithm (GOA), which is a metaheuristic optimization algorithm, has been recently developed by Saremi et al. (2017). This algorithm mathematically models and mimics the behaviour of grasshopper swarms in nature for solving the optimization problems. [4,5] It has been successfully applied to various benchmark and real-world problems [6-8].

The steps in the procedure of GOA are shown below. They are as follows: [4]

Step 1: Initialize the problem and algorithm parameters
Step 2: Initialize the swarm
Step 3: Calculate the fitness (objective function) of each search agent (grasshopper)
Step 4: For each search agent: normalize the distances between search agents, update the position of the current search agent, bring the current search agent back if it goes outside the boundaries
Step 5: Update the best search agent (update the best fitness value)
Step 6: Return best fitness value

The mathematical model which is employed to simulate the behaviour of the grasshopper swarms is given below:

$$X_i = S_i + G_i + A_i \quad (48)$$

Where X_i defines the position of the i-th grasshopper, S_i represents the social interaction, G_i is the gravity force and A_i shows the wind advection. [4]

To determine the term S_i it is necessary to know the function $s(r)$ given below, which defines the social forces.

$$s(r) = f \cdot \exp\left(-\frac{r}{l}\right) - \exp(-r) \quad (49)$$

Where r is the distance, f indicates the intensity of attraction and l is the attractive length scale. This function impacts on the social interaction (attraction and repulsion) of grasshoppers. Repulsion occurs when the distance between grasshoppers is in the interval $[0\ 2.079]$. When the grasshopper is 2.079 units away from another grasshopper, there is neither attraction nor repulsion. This zone is called the comfort zone. Attraction increases from 2.079 units of distance, Figure 3. [4]

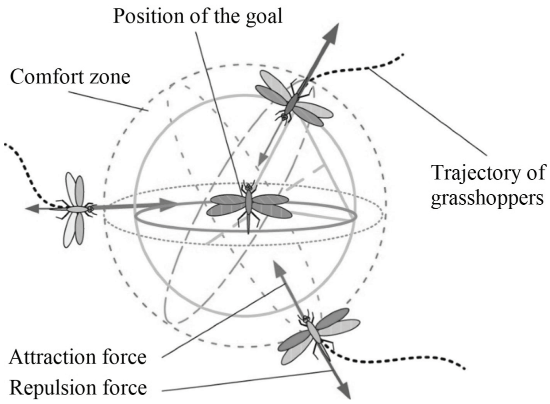

Figure 3: Corrective patterns between individuals in a swarm of grasshoppers [9]

This mathematical model cannot be used directly for optimization problems and a modified version of this equation is used to solve optimization problems in d-th dimension: [4]

$$X_i^d = c\cdot\left(\sum_{\substack{j=1\\ j\neq i}}^{N} c\cdot\frac{ub_d - lb_d}{2}\cdot s\left(\left|x_j^d - x_i^d\right|\right)\cdot\frac{x_j - x_i}{d_{ij}}\right)+\hat{T}_d \quad (50)$$

Where c is a decreasing coefficient to shrink the comfort zone, repulsion zone and attraction zone, N is the number of grasshoppers, ub_d is the upper bound in the d-th dimension, lb_d is the lower bound in the d-th dimension, x_i^d is the position of the i-th grasshopper in the d-th dimension, x_j^d is the position of the j-th grasshopper in the d-th dimension, d_{ij} is the distance between the i-th and the j-th grasshopper and $\hat{T}_d$ is the value in the target of the d-th dimension, i.e. the best solution found so far. [4]

6. NUMERICAL EXAMPLE

To test the developed model of GMA welding parameters optimization, the data used in the example are presented in Table 1.

The goal was to find the optimal values of the welding parameters that will lead to the lowest total costs of welding the butt joint of P355GH steel plates (Figure 2).

In this algorithm, the Penalty method was used for dealing with constraints. [11]

In the proposed grasshopper optimization algorithm, a population of $N = 100$ search agents were considered. The optimized values presented here were obtained after 250 iterations and 337.4 s. The values of the parameters f and l were 0.5 and 1.5, respectively. The maximum and minimum value of the coefficient c was: $c_{\max} = 1$ and $c_{\min} = 0.00004$. Table 2 shows the optimized values of the welding parameters obtained with GOA and the value of the total costs as well as all three partial costs.

7. CONCLUSIONS AND FUTURE RESEARCH

In this study, application of grasshopper optimization algorithm for optimization of GMA welding parameters has been investigated. The optimum values of welding parameters including seam overhang coefficient, degree of mixing, number of passes and welding current are obtained to yield minimum total welding costs. Based on the optimized values of the welding parameters, it can be seen that three of them are at their limit allowed values. This is consequence of the shape of the objective function itself, which is relatively simple. The GOA which is a recently developed optimization algorithm has been used as an effective tool. The ability of the algorithm is demonstrated on an illustrative example, where it showed a high speed of finding the optimum.

In future research, it is possible to include all GMA welding costs (power source, accessories and worker’s personal income costs), as well additional technological and other constraints. Also, the costs can be determined for a more complex welded joint with several different types of seams (grooves).

Table 1: Numerical data of the GMA welding costs problem [1-3,10]

Parameter	Value	Unit
Plate thickness, δ	0.015	m
Root spacing, c	0.003	m
Root blunting, h	0.005	m
Groove opening angle, φ	45	°
Constant, d_1	0.005	m
Constant, d_2	0.0015	m
Seam length, $l_š$	0.25	m
Density of filler material, ρ_e	7800	kg/m^3
Specific productivity of filler material, η_e	1.02	–
Filler material price, C_{DM}	187	RSD/kg
Shielding gas flow (CO_2), Q_a	9.17	l/min
Shielding gas price (CO_2), C_a	144	RSD/l
Preparatory-final time coefficient, k_{pz}	0.065	–
Auxiliary time, t_p	1.2	min
Electric energy price, C_s	12.06	RSD/$(\mathrm{kW}\cdot\mathrm{h})$
Coefficient of utilization of power source, η_s	0.8	–
Power source intermittency, ε	0.6	–
Idle power of source, P_0	1	kW
Constant, k	$1/2.9$	–
Constant, n	1.7	–
Constant, s_0	13	mm
Constant, α	3.5	–
Constant, T_{sr}	600	$^\circ$C
Constant, β	1	–
Constant, T_0	20	$^\circ$C
Carbon content, C	0.2	%
Silicon content, Si	0.19	%
Manganese content, Mn	1.45	%
Niobium content, Nb	0.014	%
Cu, Ni, Cr, Mo, V	0	%
Carbon content, $\mathrm{C_p} = \mathrm{C}$	0.2	%
Parameter, ΔH	0	%

Table 2: The GOA results

Optimized values of parameters			
ζ	γ	i	I_z
10	0.1	5	420
Costs values RSD			
T_{DM}	T_{ZA}	T_{ES}	T_U
25.1	2964.4	1.4	2990.9

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