Robust model-based multicriterial optimization strategies for electron beam welding of Steel 45

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In this paper an experimental study of the geometrical characteristics of the cross-sections of the thermally affected areas obtained by electron beam welding joints of carbon steel grade 45 is made. The thermally affected and the molten zones of the welds of non-stainless steels correspond to the areas where the physical-mechanical properties and the microstructure of the processed material are changed after the processing. The influence of the following welding process parameters: the welding speed, the electron beam current and the focus position, was investigated during the experiments. The geometry of the welds in the cases of a deep penetrating electron beam and narrow thermally affected zone is investigated. Electron beam welding process multicriterial parameter optimization is performed, based on the estimation of regression models and applying the robust engineering approach for production conditions. Thus, the electron beam welding equipment can be tested and specific quality requirements for the welds obtained by electron beam welding can be fulfilled.

Keywords – electron beam welding, multi-criteria optimization, optimization strategies, robust engineering design, steel 45.

Introduction

The electron beam welding (EBW) process is a flexible and cost-effective manufacturing tool for production of high quality, deep (and narrow) welds with minimal thermally-affected zone without (or with) the use of welding consumables. The high vacuum typically required by the method prevents the heated and melted material from oxidizing and being affected by atmospheric contamination. With the development of advanced computer control, the number of electron-beam applications has increased significantly. The technological data gathered during the investigation stage and during the production process enables the monitoring, optimization and increase in the repeatability of the quality of the manufactured components and supports the testing process by reducing the needed for quality validation tests and by definition of the characteristics of a given EBW equipment, the product parameters' best tolerance limits and production process stability in time.

Continuous quality improvement is a critical concept in maintaining a competitive advantage in the market for any industry. The quality improvement activities have proven their efficiency and cost-effectiveness especially when they are implemented during the design stage. The primary goal of Robust product design or Robust engineering design methodology is to determine the best process parameter settings by minimizing product quality characteristics' performance variability and biases or the deviations from their target values.

Industrial use of carbon (0.45 wt.%) Steel 45 (ASTM A570 (gr.45)) is connected with the production of gear shafts, crankshafts and camshafts, gears, spindles, cylinders, cams and other parts that are normalized, improved and subjected to surface heat treatment, and which require increased strength (HB 10^{-1} = 170 ÷ 240 MPa). Steel 45 is difficult for welding and special welding methods are applied, requiring heating and subsequent heat treatment. The chemical composition of Steel 45 in wt.% is: C is in the region 0.42 ÷ 0.5; Si - 0.17 ÷ 0.37; Mn 0.5 ÷ 0.8; Ni – max. 0.25; S – max. 0.04; P max. 0.035; Cr - max. 0.25; Cu – max. 0.25; As – max. 0.08 [1].

An experimental study of the geometrical characteristics of the cross-sections of the thermally-affected areas obtained by electron beam welding of carbon steel grade 45 is performed [1]. The thermally affected zone and the molten area of the welds from non-stainless steels corresponds to a zone where the physical-mechanical properties and the microstructure of the processed material are changed after the processing. The process parameters that were changed during the experiments are: welding speeds, the beam current and the focus position. The geometry of the weld in the cases of a deep penetrating electron beam and narrow thermally affected zone is investigated. In this paper electron beam welding process multicriterial parameter optimization is performed, based on the estimation of regression models and applying the robust engineering approach for production conditions. In such way the electron beam welding equipment can be tested and specific technological quality requirements for the welds obtained by electron beam welding can be fulfilled.

Robust engineering approach

Robust or not sensitive to noises and errors engineering approach can be implemented when analyzing experiments during which the variance is non-homogeneous over the factor (process parameters') space and when the noise factors cannot be identified nor an experiment to study them can be conducted [2, 3]. The observations in this case are called heteroscedastic (variance varies with the factor levels). This is the situation, when the analyzed data are obtained under production conditions. In order to estimate the variances of the quality characteristics there are several approaches. In the current investigation the models for the mean values and the variances of the quality characteristics of the product, are estimated by performing repeated observations. Multicriterial parameter optimization in terms of obtaining repeatability of the product parameters and quality improvement at the same time is performed by minimization of variations of the quality characteristics and fulfilling the technological requirements for these characteristics in production conditions simultaneously.

The model-based robust design approach for improving the quality of the electron beam welding process is applied. For each of the quality performance characteristics, using their regression models, two other models are estimated - for their mean values and variances in production conditions, considering the heteroscedasticity of the observations due to errors in the factor levels. The application of the proposed method gives the possibility to reduce the predicted variance of the responses at production conditions and in this way to improve the quality of the obtained product with minimum invested expenses. The quality improvement is performed using some overall criterion or simply by the performance characteristics variances minimization, while keeping their mean values close to their target values. The model of the mean value of the performance characteristic, which is a subject to errors is [2]:

$$(1) \qquad \tilde{\tilde{y}}(\mathrm{p}) = \mathrm{E}[y(z)] = \eta(p) + \theta^T E(g),$$

where $\eta(p)$ is a model of the quality performance characteristic, for example polynomial regression obtained by the RSM. The second term considers the bias caused by the errors transmitted from the process parameters p to the performance characteristic $\tilde{\tilde{y}}(\mathrm{p})$, where θ^T is the vector of the coefficients in the regression model η(p). E(g) stands for the mathematical expectation of $g = h - f$, h is a vector of the regressors z in the regression model, considered as containing errors e (for any process parameter – $z_i = p_i + e_i$) and f is the regressors vector of the process parameters p. The model for the variance is [2]:

$$(2) \qquad \tilde{s}^2 = E(\theta^T \psi \psi^T \theta) + \sigma_\varepsilon^2 = \theta^T \Psi \theta + \sigma_\varepsilon^2$$

where ψ = g – E(g), is defined on the basis of the variances for each process parameters p, which can be calculated using the tolerance limits of the process parameters or on the base of replicated observations, $\Psi = \mathrm{E}(\psi\psi^T)$ depends on the structure of the regression model and the experimental design, σ_ε^2 is the estimate of the random error of the performance characteristic.

Experimental conditions

Electron beam welding (EBW) of carbon (0.45 wt.%) Steel 45 is performed [1]. The weld samples are placed at 30° towards the horizontal plane and moved by a manipulator. The sample movement results in different distances between the magnetic lens of the electron beam gun and the sample surface and it is changed in the range between 228 mm to 362 mm. In same tame the distance between the focus of the beam and the main surface of the magnetic lens of the electron gun is constant and equal to 300 mm.

The influence of the variation of the process parameters: beam current (z_1), welding speeds (z_2) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) on the geometrical characteristics of the heat-affected zones (HAZ) of the obtained welds is investigated.

The accelerating voltage is 50 kV, the electron beam current varies at four levels: 30, 66, 100 and 133 mA, and the welding speeds are: 0.5, 1 and 1.5 cm/sec. The welded specimens are steel rods with rectangular cross-sections (20 mm × 34 mm and 25 mm × 34 mm) and a length of 335 mm.

The geometrical characteristics of the heat affected zones (HAZ) of the experimentally obtained welds were studied: transverse cross-section area y_1, depth y_2, surface width y_3 and average width y_4.

Models of the mean and the variance of the quality characteristics

The obtained in [1] regression models and the statistical software QstatLab [6] are implemented for the estimation of models for the mean and variances of each of the investigated geometrical characteristics of the cross sections of the HAZ obtained by EBW of carbon steel 45 under production conditions and errors in the factor levels. In order to estimate the variance of the process parameters, their tolerance intervals, shown in Table 1, were used.

Table 1

Tolerance limits for the parameters at EBW

Parameters	Coded	Tolerance limits
Beam current [mA]	p_1	$z_1 \pm 3\% z_1$
Welding speeds cm/sec]	p_2	$z_2 \pm 5\% z_2$
Distances between the magnetic lens of the electron beam gun and the sample surface [mm]	p_3	$z_3 \pm 2$ mm

For each of the quality performance characteristics, two other models are estimated - for their mean values and variances (or standard deviations) in production conditions. The estimated models for the mean values $\tilde{\tilde{y}}_i$ and the standard deviations $\tilde{s}_i$ are illustrated in Figs. 1-4 for a distance between the magnetic lens of the electron beam gun and the sample surface of z_3 = 295 mm or the beam focus position is 5 mm below the sample surface.

In Fig. 1 and Fig. 2 are presented the dependencies of the mean values $\tilde{\tilde{y}}_2$ and the standard deviations $\tilde{s}_2$ of the HAZ depth depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec).

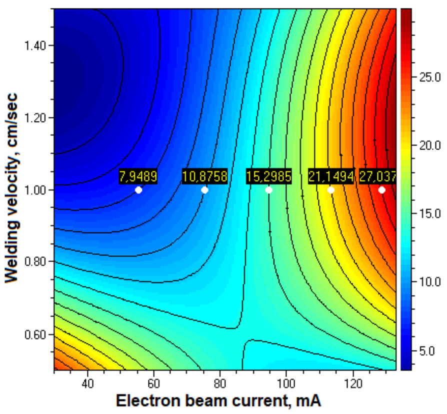

Fig. 1. Contour plot of the mean values $\tilde{\tilde{y}}_2$ of HAZ depth depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec) for a distance to the sample surface of z_3 = 295 mm.

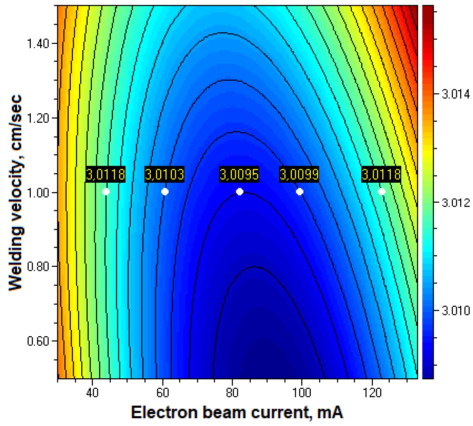

Fig. 2. Contour plot of the standard deviations $\tilde{s}_2$ of HAZ depth depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec) for a distance to the sample surface of z_3 = 295 mm.

It can be seen that at the set focus position, the maximal HAZ depth (fusion zone depth too) is obtained for highest electron beam current for welding velocities from 1 cm/sec to 1.4 cm/sec. For this region of velocities, the standard deviation (variance) can be minimized in order to obtain higher reproducibility (Fig. 2) of the depth.

In Fig. 3 and Fig. 4 are presented the dependencies of the mean values $\tilde{\tilde{y}}_3$ and the standard deviations $\tilde{s}_3$ of the HAZ surface width depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec).

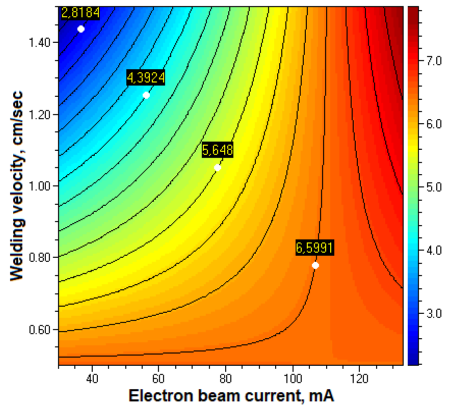

Fig. 3. Contour plot of the mean values $\tilde{\tilde{y}}_3$ of HAZ surface width depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec) for a distance to the sample surface of z_3 = 295 mm.

It can be seen that at these conditions, the regimes with minimal HAZ surface width correspond to highest standard deviations. In this case, as well as in the general multicriterial optimization case a search for compromise solutions must be applied.

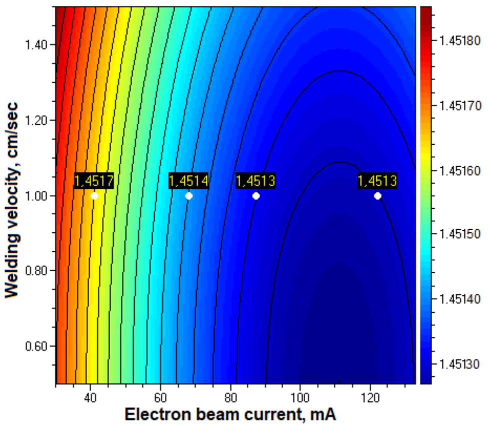

Fig. 4. Contour plot of the standard deviations $\tilde{s}_3$ of HAZ surface width depending on the variation of the electron beam current (p_1, mA) and the welding velocity (p_2, cm/sec) for a distance to the sample surface of z_3 = 295 mm.

Multicriterial optimization

Pareto-optimization is applied to find such compromise solutions that simultaneously meet the following requirements:

- $\tilde{\bar{y}}_1$ → minimum;
- $\tilde{\sigma}_1$→ minimum;
- $\bar{y}_2$ → maximum;
- $\tilde{\sigma}_2$→ minimum;
- $\bar{y}_3$ → minimum;
- $\tilde{\sigma}_3$→ minimum;
- $\bar{y}_4$ → minimum;
- $\tilde{\sigma}_4$→ minimum.

Pareto-optimal compromise solutions are obtained (50 solutions) by applying genetic algorithm and the statistical software QstatLab [6]. Each solution makes some compromise toward some or all geometrical characteristics of the cross sections of the HAZ criteria to a certain extend at the same time. If we compare randomly chosen two Pareto-optimal solutions some of the observed characteristics will have better values, but at least one will be worse. In order to choose one solution from all we need additional analysis. This choice can be done by considering additional criteria (not included in the optimization task), by evaluation based on expert opinion or by definition of an overall function like loss function, desirability function, etc.

In the present work, methods based on reference point strategies optimization are implemented for solving this task. They are compered by estimation of the overall relative error for all best solutions that are obtained.

Optimistic strategy

The *optimistic strategy* is based on the method of the function of losses. This optimization approach is called "optimistic" because the best possible values q_j^{Opt} (j = 1, 2, 3, …, m) are assigned to the reference (uncompromised) values of the observed geometrical characteristics of the cross sections of the HAZ - $q_i(p)$. The reference values depend on the required minimum or maximum value for each of the quality characteristics. They are determined from the obtained Pareto-optimal solutions or in this case the differences between the best values and the optimistic reference values are minimized. The generalized function of losses $F^{Opt}(p)$ that has to be minimized is [7]:

$$F^{Opt}(p) = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{q_j^{Opt} - q_j(p)}{\Delta_j}\right)^2, \quad (3)$$

$$\Delta_j = q_{max,j} - q_{min,j}, \quad (4)$$

where $q_j(p)$ is the value for the j-th observed characteristic obtained at a given Pareto-optimal solution, $q_{max,j}$ and $q_{min,j}$ are the maximal and minimal values of each characteristic from all obtained 50 Pareto-optimal solutions and are presented in Table 2, together with calculated value for Δ_j. Each reference value q_j^{opt} is obtained usually for different set of optimal process parameters z_i and cannot be obtained simultaneously.

Table 2

Goals, reference values and the maximal and minimal characteristic values $q_j(p)$.

Param.	$\tilde{\bar{y}}_1$ mm	$\tilde{\sigma}_1$ mm^2	$\tilde{\bar{y}}_2$ mm	$\tilde{\sigma}_2$ mm	$\tilde{\bar{y}}_3$ mm	$\tilde{\sigma}_3$ mm	$\tilde{\bar{y}}_4$ mm	$\tilde{\sigma}_4$ mm
Goal	min ↓	min ↓	max ↑	min ↓	min ↓	min ↓	min ↓	min ↓
q_j^{Opt}	3.30	17.33	29.84	3.01	0.01	1.45	0.02	1.66
q_j^{Pes}	136.98	17.36	5.26	3.02	10.69	1.45	12.35	1.66
$q_{j,max}$	136.98	17.36	29.84	3.02	10.69	1.45	12.35	1.66
$q_{j,min}$	3.30	17.33	5.26	3.01	0.01	1.45	0.02	1.66
Δ_j	133.68	0.03	24.56	0.01	10.67	0.001	12.32	0.001

The best 5 optimal solutions obtained by implementation of the *Optimistic method* are presented in Table 3. They have smallest values of the function of losses $F^{Opt}(p)$ from the arranged in ascending order results from all obtained 50 Pareto-optimal solutions (their numbers are kept in the table). It can be seen that the best result, obtained for $F^{Opt}(p)$ = 0.0987 is obtained for Pareto-optimal solution № 47, as well as the optimal values of the process parameters (z_i) at which it can be obtained in production conditions.

Pessimistic strategy

The pessimistic strategy is based on the function of usefulness method. In this strategy the worst possible (among the obtained Pareto-optimal solutions) or the "pessimistic" values q_j^{Pes} (*j = 1, 2, 3, ..., m*) are assigned as reference values of the observed geometrical characteristics of the cross sections of the HAZ - $q_i(p)$, again depending on the required minimum or maximum value for each quality characteristic from Pareto-optimal solutions. The function $F^{Pes}(p)$ that has to be maximized is [7]:

$$F^{Pes}(p) = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{q_j(p) - q_j^{Pes}}{\Delta_j}\right)^2 \quad (5)$$

The best 5 optimal solutions obtained by implementation of the *Pessimistic strategy* are presented in Table 4. They have largest values of the function of usefulness $F^{Pes}(p)$ from the arranged in descending order results from all obtained 50 Pareto-optimal solutions (their numbers are kept in the table).

From Table 4 can be seen that the best result, obtained for $F^{Pes}(p)$ = 0.6724 is obtained for Pareto-optimal solution № 21.

Bracketing approach for multi-criteria optimization

The bracketing multi-criteria optimization strategy combines the optimistic and pessimistic approaches. Here the optimal compromise solution is searched by simultaneously minimizing the under-achievement to the best values (reference values) q_j^{Opt} and maximizing the over-achievement over the required (worst) values q_j^{Pes} [7].

The optimization function that has to be maximized in this case is:

$$F^{Br}(p) = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{q_j(p) - q_j^{Pes}}{\Delta_j}\right)^2 - \frac{1}{m}\sum_{j=1}^{m}\left(\frac{q_j^{Opt} - q_j(p)}{\Delta_j}\right)^2 \quad (6)$$

The best 5 optimal solutions obtained by implementation of the *Bracketing strategy* are presented in Table 5. They have largest values of the function of usefulness $F^{Br}(p)$ from the arranged in descending order results from all obtained 50 Pareto-optimal solutions (their numbers are kept in the table).

It can be seen, that the best result in this case is the same as in the *Optimistic method* and it is Pareto-optimal solution № 47 and the best result, obtained for $F^{Br}(p)$ is $F^{Br}(p)$ = 0.57362.

Table 3

Best 5 optimal solutions by Optimistic strategy.

№	F^{Opt}	z_1	z_2	z_3	$\tilde{\tilde{y}}_1$	$\tilde{\sigma}_1$	$\tilde{\tilde{y}}_2$	$\tilde{\sigma}_2$	$\tilde{\tilde{y}}_3$	$\tilde{\sigma}_3$	$\tilde{\tilde{y}}_4$	$\tilde{\sigma}_4$
47	0.098748	31.22055	1.1013	231.9329	12.2964	17.3341	10.8191	3.0102	1.3278	1.4514	0.0423	1.6615
21	0.099867	32.5338	1.1395	230.1105	9.5875	17.334	10.5639	3.0102	1.1203	1.4514	0.0188	1.6615
42	0.106398	36.22635	0.5706	239.3833	81.8307	17.333	24.7109	3.0097	4.5171	1.4514	2.1755	1.6616
19	0.112690	50.27555	0.7065	253.8084	44.974	17.3326	15.1213	3.0093	5.2795	1.4514	3.6495	1.6615
13	0.119735	38.549	0.99735	251.1552	17.7999	17.3328	9.2938	3.0098	3.5741	1.4514	2.3793	1.6614

Table 4

Best 5 optimal solutions by Pessimistic strategy.

№	F^{Pes}	z_1	z_2	z_3	$\tilde{\tilde{y}}_1$	$\tilde{\sigma}_1$	$\tilde{\tilde{y}}_2$	$\tilde{\sigma}_2$	$\tilde{\tilde{y}}_3$	$\tilde{\sigma}_3$	$\tilde{\tilde{y}}_4$	$\tilde{\sigma}_4$
21	0.672368	32.5338	1.1395	230.1105	9.5875	17.334	10.5639	3.0102	1.1203	1.4514	0.0188	1.6615
47	0.662631	31.22055	1.1013	231.9329	12.2964	17.3341	10.8191	3.0102	1.3278	1.4514	0.0423	1.6615
13	0.633973	38.549	0.99735	251.1552	17.7999	17.3328	9.2938	3.0098	3.5741	1.4514	2.3793	1.6614
36	0.579756	70.84465	0.98905	293.5863	25.735	17.333	10.1318	3.0091	5.5854	1.4513	5.931	1.6615
42	0.542106	36.22635	0.5706	239.3833	81.8307	17.333	24.7109	3.0097	4.5171	1.4514	2.1755	1.6616

Table 5

Best 5 optimal solutions by Bracketing approach.

№	F^{Br}	z_1	z_2	z_3	$\tilde{\tilde{y}}_1$	$\tilde{\sigma}_1$	$\tilde{\tilde{y}}_2$	$\tilde{\sigma}_2$	$\tilde{\tilde{y}}_3$	$\tilde{\sigma}_3$	$\tilde{\tilde{y}}_4$	$\tilde{\sigma}_4$
47	0.573620	31.22055	1.1013	231.9329	12.2964	17.3341	10.8191	3.0102	1.3278	1.4514	0.0423	1.6615
21	0.562763	32.5338	1.1395	230.1105	9.5875	17.334	10.5639	3.0102	1.1203	1.4514	0.0188	1.6615
42	0.527576	36.22635	0.5706	239.3833	81.8307	17.333	24.7109	3.0097	4.5171	1.4514	2.1755	1.6616
19	0.467066	50.27555	0.7065	253.8084	44.974	17.3326	15.1213	3.0093	5.2795	1.4514	3.6495	1.6615
13	0.422372	38.549	0.99735	251.1552	17.7999	17.3328	9.2938	3.0098	3.5741	1.4514	2.3793	1.6614

In order to compare the implemented optimization strategies: *Optimistic and Pessimistic/Bracketing approaches*, the absolute errors are calculated for the best-chosen compromise solutions by an equation (7):

$$\delta_{aj} = \left|q_{j,opt}(p) - q_j^*(p)\right| \quad (7)$$

where $q_j^*(p)$ is the best value from all Pareto-optimal solutions for the *j-th* quality characteristic, coinciding with the reference point of the optimistic approach. The relative error in this case can be calculated by an equation (8):

$$\delta_{rj} = \frac{\delta_{aj}}{\Delta_j} * 100\% \quad (8)$$

The calculated results are presented in Table 6.

Table 6

Comparison of implemented optimization strategies.

Param.	$\tilde{\tilde{y}}_1$ mm	$\tilde{\sigma}_1$ mm^2	$\tilde{\tilde{y}}_2$ mm	$\tilde{\sigma}_2$ mm	$\tilde{\tilde{y}}_3$ mm	$\tilde{\sigma}_3$ mm	$\tilde{\tilde{y}}_4$ mm	$\tilde{\sigma}_4$ mm
Goal	min ↓	min ↓	max ↑	min ↓	min ↓	min ↓	min ↓	min ↓
q_j^*	3.30	17.33	29.84	3.01	0.01	1.45	0.02	1.66
Δ_j	133.68	0.03	24.56	0.01	10.67	0.001	12.32	0.001
$q_{j,opt}$, *Opt/Br*	12.296	**17.334**	**10.82**	**3.01**	1.338	**1.45**	0.04	**1.662**
δ_{aj}	9.001	0.002	19.02	0.002	1.316	0.0001	0.024	0.0001
δ_{rj},%	6.73	7.79	77.41	25	12.32	25	0.19	20
$q_{j,opt}$, *Pes*	**9.5875**	**17.334**	10.564	**3.01**	**1.12**	**1.45**	**0.019**	**1.662**
δ_{aj}	6.2914	0.0023	19.273	0.002	1.108	0.0001	0	0.0001
δ_{rj},%	4.71	7.47	78.45	25	10.38	25	0	20

From Table 6 can be seen that the implemented strategies give very close results. The only quality parameter, which is a little better for the solution, given by the *Optimistic* or *Bracketing strategies*, is the result for the mean value of the geometrical characteristic depth of the HAZ - $\tilde{\tilde{y}}_2$.

All the other criteria values are better or equal for the case of implementation of the *Pessimistic approach*.

Conclusion

In this paper, three multicriteria optimization approaches were applies and compared, aiming to simultaneously fulfil the requirements for the geometric characteristics of the HAZ during the electron beam welding of carbon steel grade 45 samples.

The comparison of obtained best working regimes of the applied multi-criteria optimization strategies give close results. The biggest compromise is done with the HAZ depth mean $\tilde{\tilde{y}}_2$, which is around 77%-78% from the region of the optimal values of obtained Pareto-optimal solutions.

If the technological requirements are set by certain target value of the weld (HAZ) depth, the optimization approaches should be set in order to minimize all the other criteria, while keeping the depth value equal to the target value. In this way the quality of the welded samples will be improved in terms of variance and repeatability in production conditions.

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