Optimization of the electron beam welding of Steel 45 samples

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Abstract: *An experimental study of the geometrical characteristics of the cross sections of the thermally affected areas obtained by electron beam welding of carbon steel 45 is made. 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 were 0.5, 1.0 and 1.5 cm/sec, the beam current was changed in the range of 30 - 133 mA and the focus position was changed from 72 mm above the sample surface to 62 mm below the sample surface. The accelerating beam voltage was 50 kV. The geometry of the weld in the cases of a deep penetrating electron beam and narrow thermally affected zone is investigated. Electron beam welding process parameter optimization is performed, based on the estimation of regression models. In such way the electron beam optical systems can be tested and the specific quality requirements for the welds obtained by electron beam welding can be fulfilled.*

Keywords*: ELECTRON BEAM, WELD, HEAT-AFFECTED ZONE, REGRESSION ANALYSIS, OPTIMIZATIONS, STEEL 45*

1. Introduction

Industrial use of carbon (0.45 wt.%) Steel 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 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.

The accelerated introduction of new powerful heat sources - electron beams and lasers, compared to conventional fusion welding technologies is due to their advantages. Current research and development in the field of electron beam welding (EBW) is mainly related to process automation and quality improvement. This complex process produces welds long before the development of the scientific explanation for deep penetrating intense electron beams in metals [1 - 3]. The [4 - 6] physical and thermal models can serve only as a basis for forecasting of the geometric parameters of the obtained seams and are not suitable for use in the automation and control of EBW installations. Good alternative for the control of the process is the implementation of statistical approach to data processing and modeling of stainless steel [7 - 10].

In this work for the research of the EBW process Response Surface Methodology is implemented. An experimental study of the geometrical characteristics of the cross sections of the thermally affected areas obtained by electron beam welding of carbon steel 45 is made. 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 (Fig. 1).

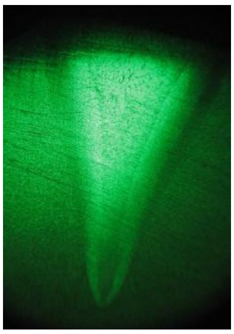


Fig. 1 *Metallographic image of an experimental weld – the welded and the heat affected zones.*

The process parameters that were changed during the experiments are: welding speeds were 0.5, 1.0 and 1.5 cm/sec, the beam current was changed in the range of 30 - 133 mA and the focus position was changed from 72 mm above the sample surface to 62 mm below the sample surface. The accelerating beam voltage was 50 kV. The geometry of the weld in the cases of a deep penetrating electron beam and narrow thermally affected zone is investigated. Electron beam welding process parameter optimization is performed, based on the estimation of regression models. In such way the electron beam optical systems can be tested and the specific quality requirements for the welds obtained by electron beam welding can be fulfilled.

2. Experimental conditions

Electron beam welding of carbon (0.45 wt.%) Steel 45 is performed [8, 10] and the experimental conditions that are shown in Fig. 2. 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 (z_s) and it is changed in the range between 228 mm to 362 mm. In same tame the distance between the focus of the beam (marked as the distance “b” on Fig. 2) and the main surface of the magnetic lens of the electron gun is constant and it’s 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_s – z_3) on the geometrical characteristics of the Heat Affected Zones (HAZ) of the obtained welds is investigated.

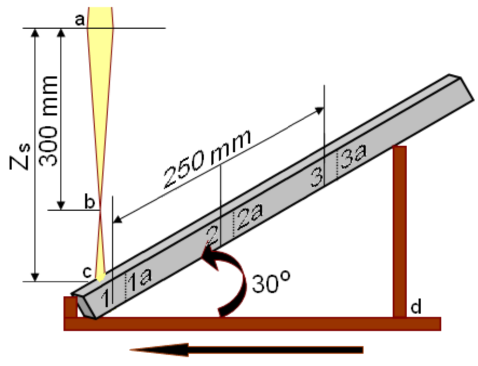
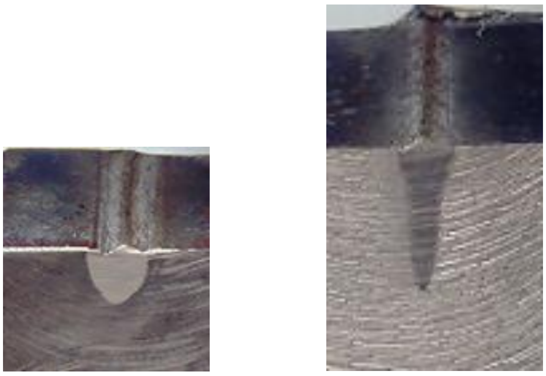


Fig. 2 *Experimental conditions: a) main surface of the magnetic lens of the electron gun; b) beam focus (or beam waist); c) surface of the sample; d) manipulator in the EBW vacuum chamber.*

The accelerating voltage is 50 kV; the 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 sections (20 mm × 34 mm and 25 mm × 34 mm) and a length of 335 mm.

The geometrical characteristics of the thermally affected areas of the experimentally obtained welds were studied: transverse cross-section area S_{HAZ}, depth H_{HAZ}, surface width B_{THAZ}, average width B_{MHAZ}, as well as the ratio of depth to surface width of the heat affected area H_{HAZ}/B_{THAZ}. This ratio is important for setting the limit for the transition from the hemispherical toward deep and narrow welds (Fig. 3), which are typical for electron beam welding process. It can be accepted that for the heat affected zone this limit is $H_{HAZ}/B_{THAZ} = 1.2$, which will correspond to a ratio of 1.5 or more for the welded zone.



a) hemispherical *b) deep and narrow*

Fig. 3 *Different shapes of the weld cross-sections.*

The conducted experiment includes 58 process parameter sets and the corresponding geometry characteristics after EBW, measured after cutting the welded rods at an angle of 30°. Regression models were estimated for the geometrical characteristics of the thermally affected areas of the electron beam welds. The natural values of the factors (z_i) in the obtained regression models are coded in the region [-1 ÷ 1] and the relation between the coded (x_i) and the natural values (z_i) is given by:

(1) $x_i = (2z_i - z_{i,max} - z_{i,min})/(z_{i,max} - z_{i,min})$,

where $z_{i,min}$ and $z_{i,max}$ are the corresponding values of the minimum and the maximum of the process parameters during the experiment.

3. Geometric characteristics of the thermally affected zones of the weld cross-sections

H_{HAZ}/B_{THAZ} is used to determine the limit value of the shape of the heat affected zone and can be used as a measure to roughly estimate the transition from a point to a linear heat source or from hemispherical toward deep and narrow welds (Fig. 3).

In order to apply the regression analysis a regression model for H_{HAZ}/B_{THAZ} ratio is estimated:

$$H_{HAZ}/B_{THAZ} = 2.2217645 + 0.71408576x_1 + 0.50453547x_2 - 1.0886828x_3^2 - 0.6469683x_2x_3^2$$

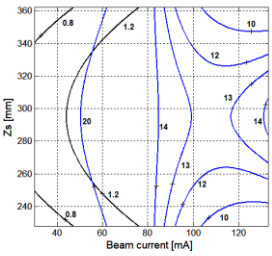
The value of the multiple correlation coefficient is $R = 0.8736$, and it is enough high and close to 1, so the estimated model for the H_{HAZ}/B_{THAZ} ratio can be considered as good enough for prediction and parameter optimization.

For the limit value of the ratio of depth to width of the surface of the thermally affected zone H_{HAZ}/B_{THAZ} the value 1.2 is accepted. The experimentally obtained results are divided into two, according to the limit value in order to increase the accuracy of the estimated models for the HAZ geometry.

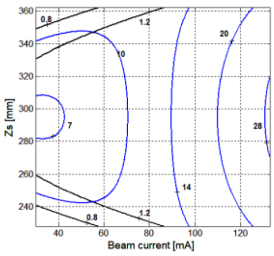
For the range in which the $H_{HAZ}/B_{THAZ} > 1.2$, regression models for the geometric characteristics of the HAZ of the electron beam welds: S_{HAZ} - the cross-sectional area, H_{HAZ} - depth, B_{THAZ} – surface (top) width and B_{MHAZ} - mean width at the middle part of the weld are estimated and are presented in Table 1, together with the values of the corresponding multiple correlation coefficients R. All coefficients are tested for significance and their values are measures of the accuracy of the estimated models. The closer to 1 the value of R is, the better the model describes the variations of the geometric characteristics of the thermally affected areas as a function of the process parameters. All models have enough high and significant values of their multiple correlation coefficients and consequently they can be used for prediction and optimization of the considered HAZ geometric characteristics.

Table 1: *Models for the geometric characteristics of the heat affected zones of the electron beam welds where $H_{HAZ}/B_{HAZ} > 1.2$.*

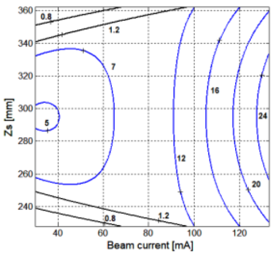
	Regression models	*R*
S_{HAZ}	$35.103301 + 56.140867x_1 - 12.464795x_2 + 42.111488x_1^2 + 36.309514x_1x_2 - 39.204101x_1x_2^2$	0.8868
H_{HAZ}	$12.089812 + 11.083831x_1 - 2.267595x_2 + 5.7456571x_1^2 - 6.7284979x_1x_3^2 - 8.7193565x_1x_2^2 + 8.2757012x_1x_2$	0.8822
B_{THAZ}	$5.8525867 + 1.4094888x_1 - 0.82996409x_2 + 1.4303279x_1x_2 + 3.118566x_1x_3^2$	0.8062
B_{MHAZ}	$6.3864563 + 2.0095741x_1 + 1.8677278x_3 + 3.1053106x_1x_3^2 - 1.6123818x_2^2x_3$	0.7541



a) z_2 = 0.5 cm/sec



b) z_2 = 1 cm/sec



c) z_2 = 1.5 cm/sec

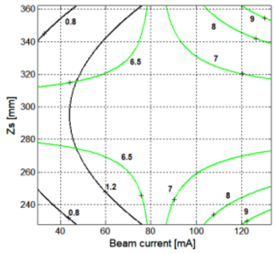
Fig. 4 *Contour plots of the depth – H_{HAZ} with blue lines and H_{HAZ}/B_{THAZ} ratio – with black lines, depending on the variation of the beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different values for the welding speeds – z_2: a) welding speeds – z_2 = 0.5 cm/sec; b) welding speeds – z_2 = 1 cm/sec and c) welding speeds – z_2 = 1.5 cm/sec.*

In Fig. 4 - 6 contour plots for the geometric characteristics of the thermally affected zones of the electron beam welds where $H_{HAZ}/B_{HAZ} > 1.2$, depending on the variation of the beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different values for the welding speeds – z_2 are presented.

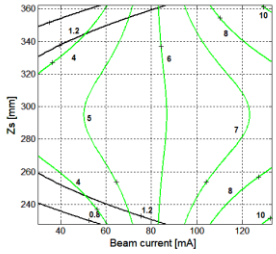
From the contour plots in Fig. 4, the depth of the HAZ of the electron beam welds – H_{HAZ} is shown with blue lines. It can be seen that the maximum welding depth can be obtained when the beam current (z_1) is at its maximum, the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) are between 280 mm and 320 mm and the welding speed is z_2 = 1 cm/sec (Fig. 4b).

In Fig. 5 and Fig. 6 on the contour plots the top surface width of the HAZ of the electron beam welds – B_{THAZ} is marked with green lines and the mean width – B_{MHAZ} - with red lines.

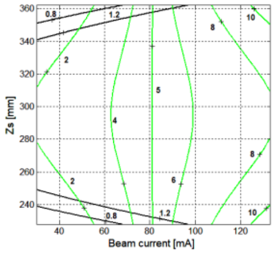
In order to obtain welds with small depts the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) should be between 280 mm and 320 mm, the beam current (z_1) has to be less than 60 mA for all considered cases.



a) z_2 = 0.5 cm/sec

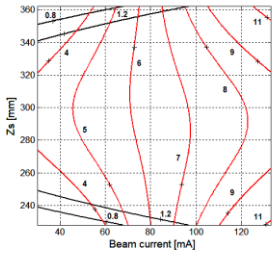


b) z_2 = 1 cm/sec

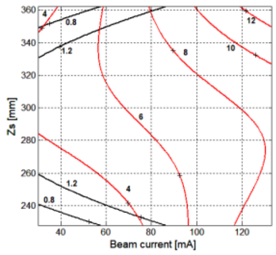


c) z_2 = 1.5 cm/sec

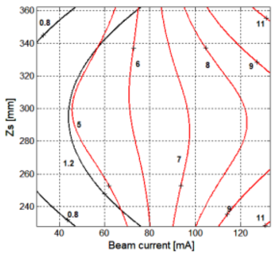
***Fig. 5** Contour plots of the surface width of the thermally affected areas of the electron beam welds – B_{THAZ} with green lines and H_{HAZ}/B_{THAZ} ratio – with black lines, depending on the variation of beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different values for the welding speeds – z_2: a) welding speeds – z_2 = 0.5 cm/sec; b) welding speeds – z_2 = 1 cm/sec and c) welding speeds – z_2 = 1.5 cm/sec.*



a) z_2 = 0.5 cm/sec



b) z_2 = 1 cm/sec



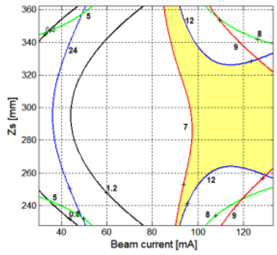
c) z_2 = 1.5 cm/sec

***Fig. 6** Contour plots of the mean width – B_{MHAZ} in red line and H_{HAZ}/B_{THAZ} ratio – with black lines, depending on the variation of beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different values for the welding speeds – z_2: a) welding speeds – z_2 = 0.5 cm/sec; b) welding speeds – z_2 = 1 cm/sec and c) welding speeds – z_2 = 1.5 cm/sec.*

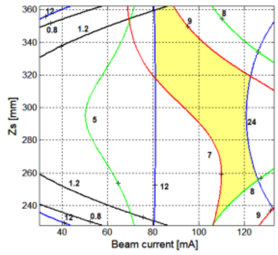
4. Optimization

Multi-criteria optimization unifying the requirements for obtaining narrow and deep welded joints is performed. Methods based on graphical optimization and on Pareto-optimization are implemented for solving this task.

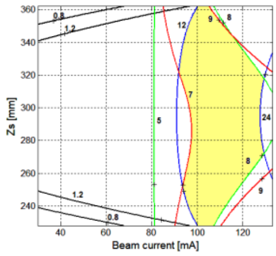
Graphical optimization is a method for multi-criteria optimization, applicable in cases with formulated one- or two-sided constraints for the product quality characteristics. It is conducted in order to find the regions of the process parameters, working at which the requirements for the quality characteristics are fulfilled simultaneously.



a) z_2 = 0.5 cm/sec



b) z_2 = 1 cm/sec



c) z_2 = 1.5 cm/sec

***Fig. 7** Contour plots of the optimal regions of the process parameters: beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different welding speeds – z_2: a) welding speeds – z_2 = 0.5 cm/sec; b) welding speeds – z_2 = 1 cm/sec and c) welding speeds – z_2 = 1.5 cm/sec, where the depth – H_{HAZ} is with blue color, the surface width - B_{THAZ} – green, the mean width - B_{MHAZ} – red and the H_{HAZ}/B_{THAZ} ratio - black.*

The graphical multi-criteria optimization was used to find operating modes that meet the following technological requirements (constraints) for the HAZ of the welds:

- 12 mm $\leq H_{HAZ} \leq$ 24 mm;
- 5 mm $\leq B_{THAZ} \leq$ 8 mm;
- 5 mm $\leq B_{MHAZ} \leq$ 9 mm.

In Fig. 7 the optimal regions (yellow) of the process parameters values of the electron beam current (z_1) and the distances between the magnetic lens of the electron beam gun and the sample surface (z_3) for different welding speeds – z_2 are presented. From the figure it can be seen that the largest optimal region is obtained when the welding speed is at its largest value z_2 = 1.5 cm/sec (Fig. 7c).

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

- $H_{HAZ} \rightarrow maximum$;
- $S_{HAZ} \rightarrow minimum$;
- $B_{THAZ} \rightarrow minimum$;
- $B_{MHAZ} \rightarrow minimum$.

Some of the estimated Pareto-optimal solutions are presented in Table 2. If these compromise solutions are compared two by two, one can note that some of the obtained optimal values are better but at least one value is worse than that in another compromise solution.

Table 2. *Pareto-optimization – optimal process parameters and geometric characteristics of the thermally affected areas of the electron beam welds where H_{HAZ}/B_{HAZ} > 1.2.*

№	z_1 mA	z_2 cm/sec	z_3 mm	S_{HAZ} mm^2	H_{HAZ} mm	B_{THAZ} mm	B_{MHAZ} mm
1	42.2467	1.3457	348.8814	3.3090	7.5447	1.9131	4.2059
2	32.5647	1.04965	362	15.4821	12.2142	1.3327	3.3782
3	40.4442	0.5847	362	73.0725	24.4289	3.8794	3.0641
4	30	0.5873	228.0603	88.0395	28.1103	3.1958	0.5086
5	43.1222	1.33625	337.9805	3.2862	6.3506	2.5710	4.6671
6	30.06695	0.77475	231.3165	50.9418	19.3363	2.6482	0.1129
7	36.8495	0.88905	228	29.5067	15.0997	2.3862	0.1637
8	40.3721	0.52695	230.2244	84.3776	26.5566	4.2649	2.0532
9	36.40145	0.6078	362	74.0735	24.8426	3.5211	2.7832
10	38.7241	0.7082	228	53.4908	20.2376	3.2695	0.8197

The choice between them is usually made by adding additional criteria or by an expert opinion, depending of the formulated technological requirements.

5. Conclusions

In this work the results from the investigation, modelling and multicriteria optimization of the geometry of the heat affected zone (HAZ) of the deep weld with depth to width ratio H_{HAZ}/B_{THAZ} > 1.2 is presented. Regression models for the dependence of geometrical characteristics of the HAZ of the welds: S_{HAZ} - the cross-sectional area, H_{HAZ} - depth, B_{THAZ} - surface width and B_{MHAZ} - mean width on the EBW 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) are estimated. Optimal results (regions and Pareto-optimal regimes) for the process parameters are obtained at setting specific requirements for the geometry of the welded samples.

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