Optimization of electron beam welding of Ti-6Al-4V thin plates

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In this paper the electron beam welding of Ti–6Al–4V thin plates is simulated by implementation of a moving linear heat source model. The simulation results are used for estimation of regression models for the dependencies of molten pool geometry characteristics on the electron beam welding process parameters: electron beam power, welding velocity and the plate thickness. The optimization of electron beam of welding is considered in terms of minimization of the fusion zone geometrical parameters length, width and transverse cross-section area.

Keywords – electron beam welding, optimization, fusion zone geometry, thin plates, Ti-6Al-4V.

Introduction

The wide area of applications of the titanium alloy Ti-6Al-4V (almost 90% titanium, 6% aluminum, 4% vanadium, maximum 0.25% iron and maximum 0.2% oxygen) includes the military, aviation and aerospace industries, additive manufacturing, medical and biomedical industries. It is used in the structural components of aircraft, hydraulic systems, engine components, helicopter rotor blades, rockets and spacecraft. This is determined by the excellent properties of this titanium alloy [1, 2] - high tensile strength, high corrosion resistance (due to the titanium oxide surface layer), low modulus of elasticity, low density (light weight), easy processing - heat treatment, weldability and fabricability. The biocompatibility and non-magnetic properties of Ti-6Al-4V determine its applications for body implants, medical equipment and surgical devices.

Titanium and its alloys (in particular Ti-6Al-4V alloy) are reactive materials and can form stable oxides during their thermal processing or usage.

The advantages of processing of Ti-6Al-4V by the electron beam welding (EBW) technology are the following: EBW is typically performed in high vacuum, which prevents the heated and melted material from oxidizing and from interactions with atmosphere's pollutions, thus giving the possibility to process reactive metals and their alloys (titanium, etc.); the high power density of the electron beam ensures deep penetration in the work-piece, generating a narrow weld with minimal thermally-affected zone and without the usage of welding consumables. The geometry of the molten pool and the thermally affected zone, as well as the occurrence of defects and the change of the mechanical properties of the welded samples depend on a large number of parameters, describing the processed material, the characteristics of the electron beam equipment, as well as the technological process itself [3, 4].

In this paper the simulation of electron beam welding of Ti–6Al–4V thin plates by a moving linear heat source, using Rosenthal's solution [5], is considered. Regression models for the molten pool geometry characteristics, depending on the electron beam power, the welding velocity and the sample thickness are estimated.

Pareto-optimization methodology [6] is implemented aiming minimization of the fusion zone geometrical parameters length, width and transverse cross-section area.

Experimental conditions and simulation results

The solution of the thermal balance steady-state model involving a linear, uniformly distributed heat source in the moving with the beam respectively to sample coordinate system at heating a sheet of thickness h in these conditions assuming no phase changes in the sample during treatment is [5]:

$$T(r,x) = \frac{P}{2\pi\lambda h} \cdot e^{-\frac{Vx}{2a}} \cdot K_0\left(\frac{Vr}{2a}\right) + T_0, \quad (1)$$

where r is radius-vector from the heat source to the studied point, x and y are the coordinates in a moving together with the heat source coordinate system, (x is the axis coinciding with the direction of electron beam movement, y is the distance from this axis), λ and a are the sample thermal conductivity and diffusivity ($a = \lambda/C_p\rho$, where C_p is the specific heat and ρ is the sample density), $K_0(Vr/2a)$ is the modified Bessel function of second kind of order zero, P is the electron beam absorbed energy input (beam energy P_b after correction for energy losses by back scattered and secondary electrons), V is the welding speed, h is the sample thickness and T_0 is the initial sample temperature.

The electron beam welding is performed for 0.5 – 1.5 mm Ti–6Al–4V thin plates with dimensions of 60 mm × 100 mm. The chosen regions for the variation of the process parameters are presented in Table 1, where z_1 is power of the electron beam, z_2 is the welding velocity and z_3 is the plate thickness.

Table 1

Process parameter variation regions

Factor z_i	Dimension	Coded	Lower level ($z_{min,i}$)	Upper level ($z_{max,i}$)
z_1	W	x_1	600	900
z_2	mm/sec	x_2	15	25
z_3	mm	x_3	0.5	1.5

The transformation from natural (z_i) into coded (x_i) in the range from -1 to 1 values of the process parameters is done using the formula:

$$x_i = \frac{2z_i - (z_{max,i} + z_{min,i})}{z_{max,i} - z_{min,i}} \quad (2)$$

In order to investigate the change in the temperature distributions in the samples of Ti–6Al–4V thin plates, optimal composite design with a central point with 3 levels of the process parameters is performed. The experimental conditions in coded and natural values of the realized 15 experimental runs are given in Table 2.

The initial temperature T_0 for all experiments is 20 °C. For the EBW of Ti–6Al–4V thin plates simulation experiments the Desktop Weld Optimization Software for automated welding – SmartWeld is used [7].

The obtained results for the geometrical characteristics of the molten pool: y_1 – molten pool length (mm) along the axis x, y_2 – molten pool width (mm) along the axis y and y_3 – molten pool transverse cross-section area (mm^2) in y-z plane are presented in Table 2.

Table 2

Experimental design and obtained results for the geometric characteristics of the melted zone during EBW 0f Ti-6Al-4V thin plates

№	Coded values			Natural values			Welding pool geometry		
	x_1	x_2	x_3	z_1	z_2	z_3	y_1	y_2	y_3
1	-1	-1	-1	600	15	0.5	14.3	7.43	3.71
2	1	-1	-1	900	15	0.5	31.8	12	6.01
3	-1	1	-1	600	25	0.5	8.6	4.46	2.23
4	1	1	-1	900	25	0.5	19.1	7.21	3.61
5	-1	-1	1	600	15	1.5	1.4	1.26	1.89
6	1	-1	1	900	15	1.5	3.52	2.74	4.11
7	-1	1	1	600	25	1.5	0.837	0.755	1.13
8	1	1	1	900	25	1.5	2.11	1.64	2.46
9	0	0	0	750	20	1	4.2	2.93	2.93
10	-1	0	0	600	20	1	2.64	2.05	2.05
11	1	0	0	900	20	1	6.08	3.81	3.81
12	0	-1	0	750	15	1	5.6	3.91	3.91
13	0	1	0	750	25	1	3.36	2.34	2.34
14	0	0	-1	750	20	0.5	16.7	7.3	3.65
15	0	0	1	750	20	1.5	1.77	1.48	2.23

Modelling of the geometrical characteristics of the welds

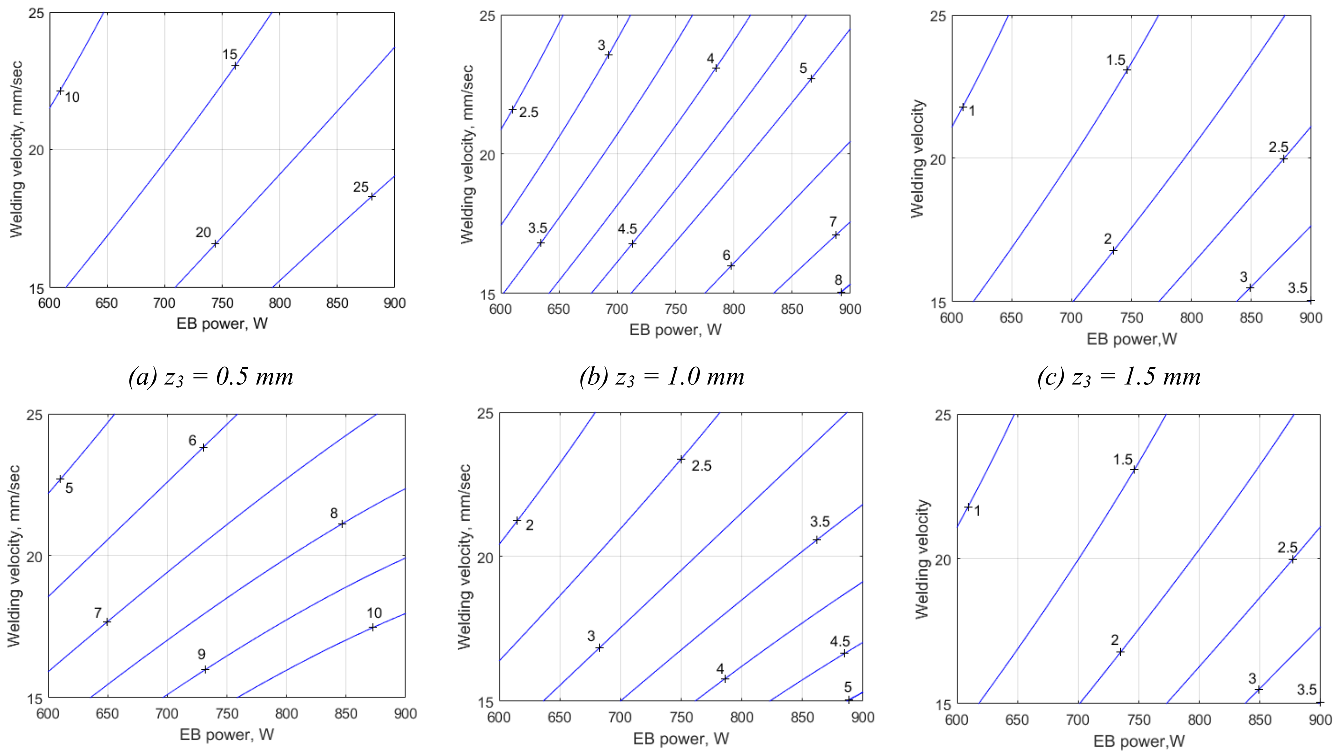
The experimental results for the molten pool geometry in Table 2 are used for the estimation of regression models giving the relationship of the geometrical characteristics and the process parameters electron beam power x_1, the welding velocity x_2 and the thickness of the plate x_3 (coded values). The estimated regression models are given in Table 3, together with the values of the corresponding determination coefficients R^2 [8, 9].

Table 3

Estimated regression models

Param.	Regression model	R^2, %
$\ln(\hat{y}_1)$	$1.437+0.428x_1-0.256x_2-1.130x_3-0.049x_1^2+0.030x_2^2+0.256x_3^2+0.031x_1x_3$	99.997
$\ln(\hat{y}_2)$	$1.074+0.313x_1-0.256x_2-0.810x_3-0.046x_1^2+0.033x_2^2+0.116x_3^2+0.074x_1x_3$	99.995
$\ln(\hat{y}_3)$	$1.075+0.314x_1-0.256x_2-0.261x_3-0.047x_1^2+0.032x_2^2-0.027x_3^2+0.074x_1x_3$	99.975

This coefficient is tested for significance and its value is a measure for the accuracy of the estimated models. From Table 3 it can be seen that all regression models are very good, the values of their determination coefficients R^2 are high (maximal value is 100%). They are significant and consequently they are good for prediction, investigation and optimization of the considered geometrical characteristics of the welds.



(a) z_3 = 0.5 mm *(b) z_3 = 1.0 mm* *(c) z_3 = 1.5 mm*

(d) z_3 = 0.5 mm *(e) z_3 = 1.0 mm* *(f) z_3 = 1.5 mm*

Fig. 1. Contour plots of the molten pool length $\hat{y}_1$ (mm) along the x-axis (a, b, c), the molten pool width $\hat{y}_2$ (mm) along the y-axis (d, e, f) as a function of the electron beam power z_1 and the welding velocity z_2 for different values of plate thicknesses z_3.

In Fig. 1 are presented contour plots of the molten pool length $\hat{y}_1$ and the molten pool width $\hat{y}_2$ as a function of the electron beam power z_1 and the welding velocity z_2 for different values of plate thicknesses z_3, using the estimated regression models in Table 3. It can be seen that the increase of the electron beam power during welding will lead to the increase of both the molten zone length and width. On contrary, the increase of the welding velocity leads to a decrease of the molten length as well as the width for all thin plate thicknesses.

EBW optimization

The estimated regression models can be applied for the optimization of EBW of Ti–6Al–4V thin plates. The optimization task depends on the concrete technological requirements, for example the plate thickness, the thermal efficiency, robustness (less sensitivity) toward errors in the controlled process parameters or other noise factors.

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

- $\hat{y}_1 \rightarrow$ minimum;
- $\hat{y}_2 \rightarrow$ minimum;
- $\hat{y}_3 \rightarrow$ minimum.

Applying genetic algorithm and the estimated regression models in Table 3, it was found that al the models for the geometry characteristics of the fusion zone reach their minimum over the considered factor space at the same optimal EBW work conditions: electron beam power z_1 = 600 W, welding velocity z_2 = 25.00 mm/sec and plate thickness z_3 = 1.5 mm.

The obtained optimal solution is presented in Fig. 2. There it can be seen the fusion zone in red color with temperatures equal or exceeding the melting temperature of Ti–6Al–4V T_{melt} = 1660 °C [7]. The accepted base metal temperature is T_0 = 20 °C. The simulated experimental output geometry parameters of the weld (the molten zone) are: length y_1 = 0.837, width y_2 = 0.755 mm and molten pool transverse cross-section area y_3 = 1.13 mm^2 (experiment 7, Table 2). The corresponding optimal values, estimated by the regression models (Table 3) are: length $\hat{y}_1$ = 0.842 mm, width $\hat{y}_2$ = 0.758 mm and molten pool transverse cross-section area $\hat{y}_3$ = 1.137 mm^2. The difference with the simulated experimental ones can be considered as negligible.

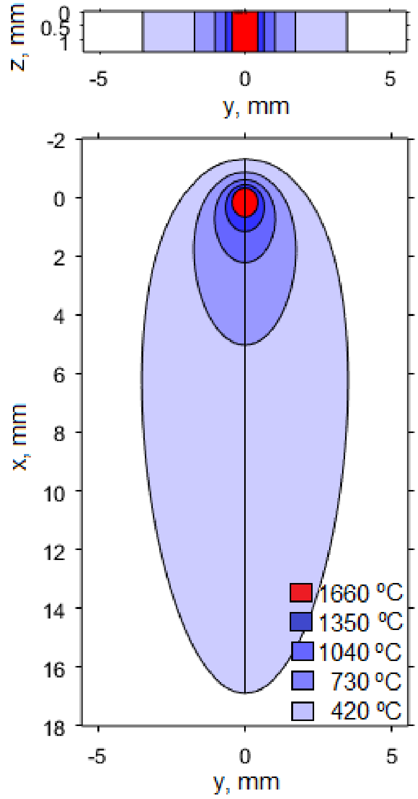


Fig. 2. Contour plots of the temperature distributions in x-y and y-z planes for electron beam power z_1 = 600 W, welding velocity z_2 = 25.00 mm/sec and plate thickness z_3 = 1.5 mm and T_0 = 20 °C

The obtained result is valid for the whole range of plate thicknesses from 0.5 mm to 1.5 mm, but for a given plate thickness, different than 1.5 mm, the result will be different for the considered ranges of electron beam powers and welding velocities.

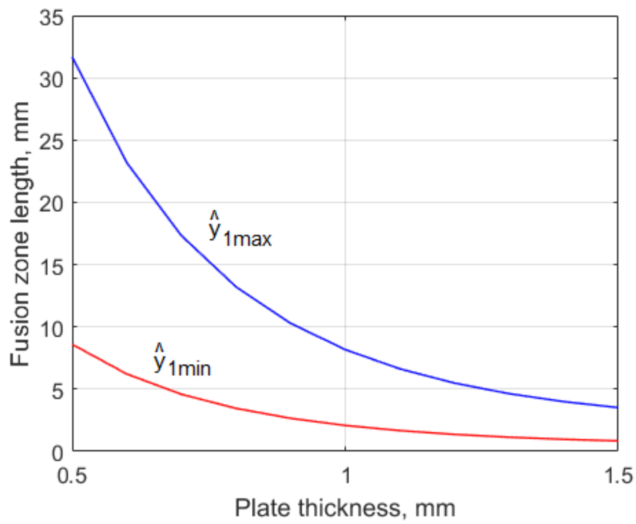


Fig. 3. Minimal fusion zone length $\hat{y}_{1min}$ and maximal fusion zone length $\hat{y}_{1max}$ depending on the plate thickness z_3.

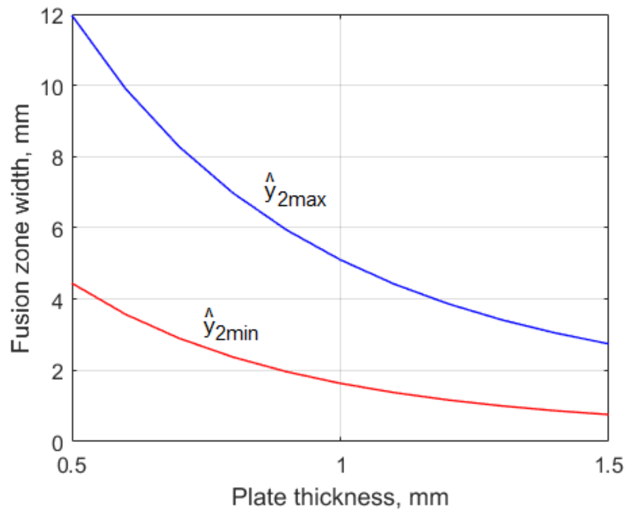


Fig. 4. Minimal fusion zone width $\hat{y}_{2min}$ and maximal fusion zone width $\hat{y}_{2max}$ depending on the plate thickness z_3.

In Fig. 3 and Fig. 4 are presented plots correspondingly for the minimal and maximal fusion zone lengths ($\hat{y}_{1\min}$ and $\hat{y}_{1\max}$) and for the minimal and maximal fusion zone widths ($\hat{y}_{2\min}$ and $\hat{y}_{2\max}$) depending on the plate thickness z_3.

For all cases the values of the EBW process parameters for obtaining minimal values of lengths and widths of the fusion zones are: electron beam power z_1 = 600 W and welding velocity z_2 = 25 mm/sec and for obtaining the maximal values - electron beam power z_1 = 900 W and welding velocity z_2 = 15 mm/sec.

The optimization of EBW of Ti–6Al–4V thin plates with defined thickness and for a given region of electron beam power and welding velocity, if it aims minimization of the fusion zone geometry parameters, can be achieved by setting the electron beam power to its minimal value and the welding velocity should be maximal.

For the achieving welds with preset requirement for the width, the estimated regression models (Table 3) and the corresponding contour plots (Fig. 1) can be used. For example, if there is a technological requirement for the width of the weld to be $\hat{y}_2$ = 1 mm and the plate thickness is z_3 = 1 mm, from the contour plot in Fig. 1e and from Fig. 4, it can be seen that it would be impossible for the considered range of electron beam powers and welding velocities. Such weld width can be achieved for example for plate thickness 1.5 mm and the corresponding regime process parameters can be chosen from Fig. 1f.

Conclusion

In this paper the simulation of electron beam welding of Ti–6Al–4V thin plates by a moving linear heat source, using Rosenthal's solution [5], is considered. Regression models for the molten pool geometry characteristics, depending on the electron beam power, the welding velocity and the sample thickness are estimated.

The optimization of electron beam of welding is considered in terms of minimization of the fusion zone geometrical parameters length, width and transverse cross-section area.

The considered optimization case study depends on the concrete technological requirements and can be combined with requirements for the thermal efficiency, for robustness (less sensitivity) toward errors in the controlled process parameters or other noise factors, etc.

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REFERENCES

[1] Veiga, C., J. Davim, A. Loureiro. Properties and Applications of Titanium alloys: A Brief Review. Rev. Adv. Mater. Sci., 32, pp. 14-34, 2012.

[2] Sibum, H., V. Gother, O. Roidl Alloys: Preparation, Properties, Applications, F. Habashi Ed., WILEY VCH Verlag GmbH, 1998, pp. 213-219.

[3] Koleva, E., G. Mladenov, Process Parameter Optimization and Quality Improvement at Electron Beam Welding, Welding: Processes, Quality, and applications, Ed. Richard J. Klein, Nova Sci. Publishers, SeriaMechanical Engineering-Theory and Applications, 2010.

[4] Tsonevska, T., E. Koleva, L. Koleva, G. Mladenov. Modelling the shape of electron beam welding joints by neural networks. Journal of Physics: Conference Series, vol. 1089, 012008, 2018.

[5] Rosenthal, D. The Theory of Moving Sources of Heat and Its Application to Metal Treatments, Transactions of the ASME, pp.849-866, November 1946.

[6] Koleva, E., L. Koleva, Dm. Trushnikov, G. Kolev, Z. Petrova. Multicriterial optimization strategies for electron beam welding process. Journal of Physics: Conference Series, 2240. 012038, 2022.

[7] Desktop Weld Optimization Software for automated welding home page SmartWeld - http://smartweld.sourceforge.net/

[8] QstatLab home page: http://www.qstatlab.co.uk/eng/index.html

[9] Koleva, E. Applied statistics. Ed. I. Vuchkov, UCTM, 2020, (in Bulgarian), 2020.

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