Simulation of electron beam welding of Inconel 718 thin plates

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In this paper the simulation of electron beam welding of Inconel 718 thin plates by a moving linear heat source is considered. Regression models for the molten pool geometry characteristics, depending on the electron beam power, welding velocity, and the thickness of the plates are estimated. These models are used for multi-criterial parameter optimization of the process electron beam welding.

Keywords – electron beam welding, Inconel 718, multi-criterial optimization, thin plates.

Introduction

Inconel 718 is a special type of high-strength superalloy with a nickel-chrome base that makes it resistant to corrosion, high pressure and extreme temperatures of up to 700 °C [1]. Other Inconel alloys are difficult to weld due to brittleness and cracking at the exact welding point. However, Inconel 718 lacks these disadvantages and electron beam welding is applied for this material. Because of its unique properties, Inconel 718 has become useful in a wide range of applications ranging from manufacturing - 3D printing, gas turbine engine parts production and die casting to military equipment and the aerospace industry.

The composition of Inconel 718 is 50-55 % nickel, 17-21% chromium, 4.75-5.5 % niobium 2.8-3.3 % molybdenum and trace amounts of, titanium, cobalt, aluminium, manganese, copper, silicon and other elements [2] and the rest content is iron.

In this paper simulation of electron beam welding (EBW) of Inconel 718 thin plates by a moving linear heat source [3, 4] is considered. Regression models for the molten pool geometry characteristics: 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 depending on the electron beam power, welding velocity, and the thickness of the plates are estimated. These models are implemented for investigation and multi-criterial parameter optimization of the process EBW.

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 [4, 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 is the coordinates in a moving together with the heat source coordinate system, this 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 thermal 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 thickness of the sample and T_0 is the initial sample temperature.

Table 1

Process parameter variation regions

Factor z_i	Dimension	Coded	Lower level ($z_{min,i}$)	Upper level ($z_{max,i}$)
z_1	kW	x_1	0.60	0.90
z_2	mm/sec	x_2	15	25
z_3	mm	x_3	0.5	1.5

The electron beam welding simulation experiments are performed for 0.5 – 1.5 mm Inconel 718 (52.5 Ni, 19 Cr, 18 Fe, 5 Nb, 3 Mo, 0.9 Ti wt% [6]) thin plates with dimensions 60 mm × 100 mm using Desktop Weld Optimization Software for automated welding – SmartWeld [6]. The chosen regions for the variation of the process parameters are presented in Table 1, where

z_1 is electron beam power, z_2 is the welding velocity and z_3 is the plate thickness.

The EBW process is performed at higher velocities aiming to avoid the appearance of big molten pools for any combination of the process parameters.

In order to investigate 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 x-y and y-z planes different sets of the process parameters are used. The realized experimental design is an optimal composite design with a central point, presented in Table 2 in coded values (x_i) in the region [-1;1] and natural values (z_i).

The investigation of the geometry characteristics of the molten pool is done by simulation of the temperature distributions in the of Inconel 718 samples (eq. 1) in the Desktop Weld Optimization Software for automated welding – SmartWeld [6].

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 x 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 geometric characteristics of the molten zone during EBW of Inconel 718 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	0.6	15	0.5	11.6	4.92	2.46
2	1	-1	-1	0.9	15	0.5	25.7	7.75	3.88
3	-1	1	-1	0.6	25	0.5	6.95	2.95	1.48
4	1	1	-1	0.9	25	0.5	15.4	4.65	2.33
5	-1	-1	1	0.6	15	1.5	1.24	1.03	1.54
6	1	-1	1	0.9	15	1.5	2.93	2	3
7	-1	1	1	0.6	25	1.5	0.746	0.617	0.925
8	1	1	1	0.9	25	1.5	1.76	1.2	1.8
9	0	0	0	0.75	20	1	3.44	2.05	2.05
10	-1	0	0	0.6	20	1	2.2	1.5	1.5
11	1	0	0	0.9	20	1	4.94	2.6	2.6
12	0	-1	0	0.75	15	1	4.59	2.74	2.74
13	0	1	0	0.75	25	1	2.75	1.64	1.64
14	0	0	-1	0.75	20	0.5	13.5	4.6	2.38
15	0	0	1	0.75	20	1.5	1.51	1.13	1.7

Fig. 1 shows the electron beam welding (EBW) simulations [6] (SmartWeld – ISO-2D) of the temperature distributions in x-y and y-z planes for electron beam power z_1 = 0.90 kW, the welding velocity z_2 = 25 mm/sec and the plate thickness z_3 = 1.5 mm (experiment № 8) and T_0 = 20 °C. The contour map of temperature contour lines is also given. The colored areas indicate temperatures exceeding that of the corresponding contour lines. In red is presented the molten zone for Inconel 718, with temperatures T ≥ 1351 °C. The electron beam movement coincides with x-axis direction.

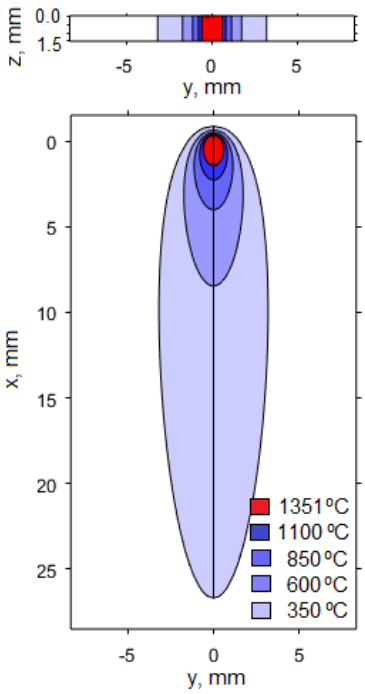

Fig. 1. Contour plots of the temperature distributions in x-y and y-z planes for electron beam power z_1 = 0.90 kW, welding velocity z_2 = 25 mm/sec and plate thickness z_3 = 1.5 mm (experiment №8) and T_0 = 20 °C.

Modelling of the geometrical characteristics of the molten zone

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 of the molten pool 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 models are estimated for the coded in the region [-1÷1] values of the process parameters, using the following equation:

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

where x_i and z_i are the coded and the natural values of the process parameter, correspondingly, $z_{i,min}$ and $z_{i,max}$ are the minimal and the maximal values of the parameter experimental variation region.

The obtained by QstatLab [7] regression models are given in Table 3, together with the square of the multiple correlation coefficient R^2 (determination coefficient) and the adjusted determination coefficient

R^2_{adj} [8]. The values of both coefficients are high (close to the maximal value of 100 %) and the estimated models can be considered as good enough for prediction, investigation and optimization of the considered geometrical characteristics of the molten pool of Inconel 718 thin plates during EBW.

Table 3

Estimated regression models

	Regression model	R^2 [%]	R^2_{adj} [%]
y_1	$3.584 + 2.799x_1 - 1.845x_2 - 6.496x_3 + 4.55x_3^2 + 1.661x_2x_3 - 2.481x_1x_3$	97.54	95.7
y_2	$2.106 + 0.718x_1 - 0.738x_2 - 1.889x_3 + 0.979x_3^2 + 0.482x_2x_3 - 0.372x_1x_3$	98.65	97.63
y_3	$2.046 + 0.571x_1 - 0.545x_2 - 0.357x_3 + 0.134x_2^2 - 0.144x_1x_2 + 0.089x_2x_3$	99.97	99.94

In Figs. 2-4 contour plots of the dependence molten pool width - y_1 (mm), molten pool length – y_2 (mm) and the molten pool transverse cross-section area – y_3 (mm^2) on the variation of the electron beam welding process parameters – electron beam power (z_1) and the welding velocity (z_2) are presented.

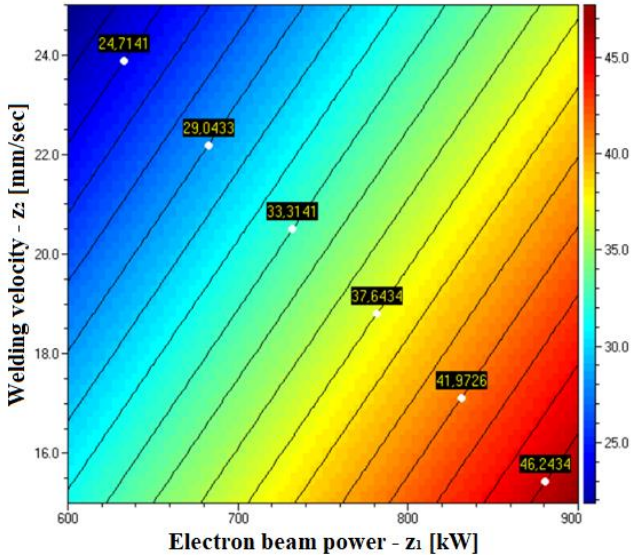

Fig. 2. Contour plot of the molten pool width – y_1 (mm) as a function of electron beam power (z_1) and welding velocity (z_2) and plate thickness z_3 = 1 mm.

From the Figs. 2 - 4 it can be seen how the increase of electron beam power increases the molten pool dimensions and on the opposite the increase in welding velocity results in molten pools with reduced dimensions.

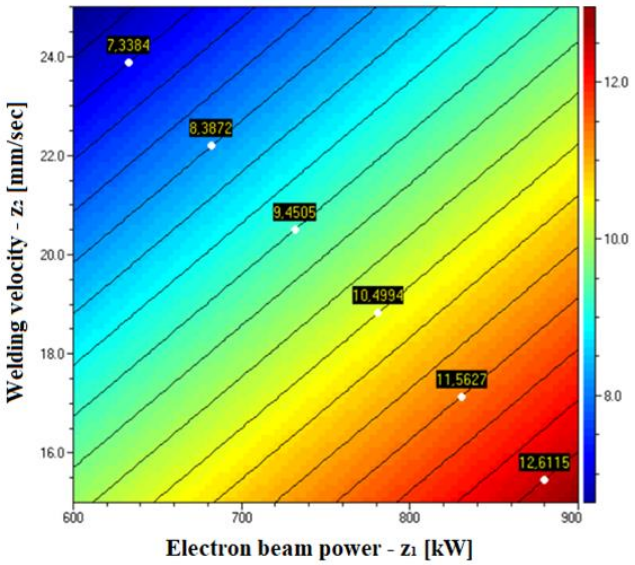

Fig. 3. Contour plot of the molten pool length – y_2 (mm) as a function of electron beam power (z_1) and welding velocity (z_2) and plate thickness z_3 = 1 mm.

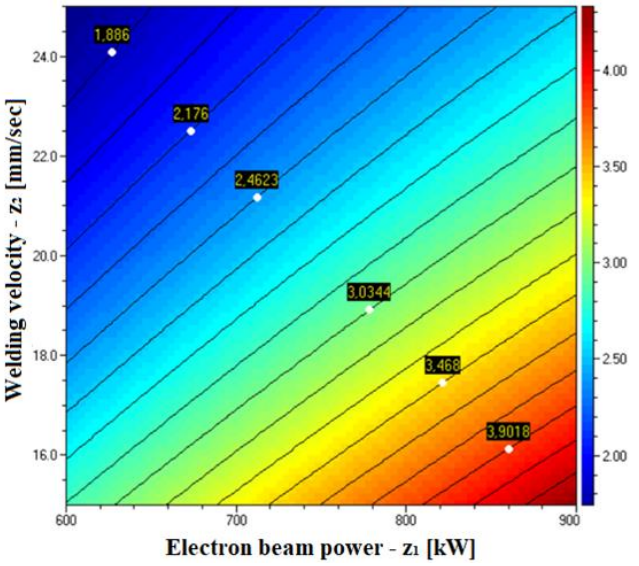

Fig. 4. Contour plot of the molten pool transverse cross-section area – y_3 (mm^2) as a function of electron beam power (z_1) and welding velocity (z_2) and plate thickness z_3 = 1 mm.

Multicriterial optimization

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

- $y_1 \rightarrow$ minimum;
- $y_2 \rightarrow$ minimum;
- $y_3 \rightarrow$ minimum.

Pareto-optimal compromise solutions are obtained (50 solutions) by applying genetic algorithm and the statistical software QstatLab. Each solution makes some compromise toward some or all quality criteria to

a certain extend at the same time. If we compare randomly chosen two Pareto-optimal solutions some of the quality characteristics will have better values, but at least one will be worse. Some of the estimated Pareto-optimal solutions, also called Pareto-front, are presented in Table 4. If these compromise solutions are compared two by two, one can note that some of the obtained optimal output values are better but at least one value is worse than that in another compromise solution.

Table 4

Pareto-optimization – optimal process parameters and molten poll characteristics

№	z_1	z_2	z_3	$\hat{y}_1$	$\hat{y}_2$	$\hat{y}_3$
1	0.6	24.99	1.403	**0.0008**	**0.4514**	0.9934
2	0.6	25.00	1.457	0.5889	0.5211	0.9647
3	0.6	25.00	1.437	0.3511	0.4917	0.9757
4	0.6	25.00	1.439	0.3756	0.4947	0.9745
5	0.6	25.00	1.420	0.1694	0.4703	0.9846
6	0.6	25.00	1.446	0.4537	0.5043	0.9708
7	0.6	24.99	1.453	0.5450	0.5157	0.9667
8	0.6	25.00	1.411	0.0794	0.4601	0.9892
9	0.6	25.00	1.468	0.7319	0.5395	**0.9584**
10	0.6	25.00	1.422	0.1998	0.4738	0.9831

From the results shown in Table 4 it can be seen that the obtained Pareto-front is very narrow and the geometry of the obtained molten pool depends mostly on the thickness of the Inconel 718 plates – z_3. The Table 4 also shows that the minimum values for the molten pool width $(\hat{y}_1)$ and length $(\hat{y}_2)$ will be obtained for solution №1, but this is also the regime with the largest molten pool transverse cross-section area. At same time the smallest molten pool transverse cross-section area $(\hat{y}_3)$ is given by Pareto-solution №9.

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

Conclusion

In this paper, the simulation of electron beam welding of Inconel 718 thin plates by a moving linear heat source is considered. Optimal composite design is performed for investigation of the influence of the process parameters: the electron beam power, the welding velocity and plate thickness on the geometrical characteristics of the molten pool – length, width and the transverse cross-section. Regression models for the molten pool geometry characteristics 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.

During validation of the obtained optimal regimes deviation of the real experiments from the simulated ones can be observed. The reasons can be different – the used thermal model for the simulation, the errors in the EBW process petameters or not considered noise factors (for example the focus position toward the sample surface), etc. Other thermal models also can be applied [9], as well as considering the thermal dependence of the thermo-physical properties of Inconel 718 [10, 11], aiming to improve the simulation accuracy. Nevertheless, the obtained results can be used for initial process parameter setting for EBW of Inconel 718 thin plates at given technological requirements. After experimental validation, model corrections (if needed) and process parameter tuning the obtained optimal settings can be used for production processing.

Acknowledgements

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