Article

Estimation of Heat Source Model's Parameters for GMAW with Non-linear Global Optimization—Part I: Application of Multi-island Genetic Algorithm

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Abstract: Estimating the thermo-elasto-plastic deformation by arc welding through finite element analysis has been used in various industrial fields. The Goldak heat source model is one of the most important and widely used models in finite element analysis, and its parameters are estimated based on the results of previous studies and tests. Part I of this study focused on the adequate heat source model, and the study for the welding deformation with the moving heat source will be done on the latter research. This study used the parameters of Goldak's heat source model, weld efficiency, and the location of the heat source as design variables, and defined the Heat Affected Zone (HAZ) boundary line of Bead on Plate (BOP) welding as the target. BOP welding was performed using SS400 plates, the HAZ boundary line was determined based on examining the shape of the cross-section, and the optimization condition was that temperature inside the boundary line exceeded 727 °C while the temperature outside the line did not exceed 727 °C during the welding process. During this process, a multi-island genetic algorithm (non-linear global optimization method) was used to obtain the optimal results out of 1000 candidate groups, in which the HAZ boundary was similar to the experimental results. Applying a global optimization algorithm to determine the parameters of the most important heat source model to analyze welding deformation is significant, and this may be applied in various industrial fields that use welding including shipbuilding, aviation, and machinery industries.

Keywords: Goldak heat source model; multi-island genetic algorithm; GMAW

1. Introduction

Welding is one of the most commonly used processing techniques in the machinery, shipbuilding, and aviation industries. Welding is a process of joining the same or dissimilar metals after raising the temperature to the melting point by using a heat source. Some of the most common welding methods are Shield Metal Arc Welding (SMAW) [1], Flux Cored Arc Welding (FCAW) [2], and Submerged Arc Welding (SAW) [3], and Gas Metal Arc Welding (GMAW) [4] is the most widely used method in most industrial fields.

Welding is a process of thermo-elasto-plastic deformation, resulting in permanent deformation. Experimental methods are often used in the field to control deformation, and computer simulations are also used to predict and respond to deformation [5–7]. Estimating the heat source is critical in welding analysis though computer simulations and many studies have been conducted on this subject. Rosenthal [8] estimated the heat source as a 1-point source, but errors occurred because the size of the heat source was infinite and the temperature-dependent material properties were not considered.

Distributed heat source models were developed such as the Gaussian heat source model and the double-ellipsoidal heat source model to overcome this problem. The Goldak model is the most

well-known double-ellipsoidal heat source model [9]. Figure 1 shows the heat distribution of the Goldak model according to Equations (1) and (2) below.

$$q_f(x, y, z, t) = \exp \left(-3 \left(\frac{(z - vt - z_0)^2}{a_f^2} + \frac{y^2}{c^2} + \frac{x^2}{b^2} \right) \right) \quad (1)$$

$$q_r(x, y, z, t) = \frac{6\sqrt{3}f_r Q}{a_r b c \pi} \exp \left(-3 \left(\frac{(z - vt - z_0)^2}{a_r^2} + \frac{y^2}{c^2} + \frac{x^2}{b^2} \right) \right) \quad (2)$$

$$f_f = \frac{2a_r}{a_f + a_r} \quad (f_f: \text{Fraction of heat deposited at the front ellipsoid}) \quad (3)$$

$$f_r = \frac{2a_f}{a_f + a_r} \quad (f_r: \text{Fraction of heat deposited at the rear ellipsoid}) \quad (4)$$

Figure 1. Heat distribution of Goldak model [9].

v—Velocity of heat source

$$Q = \mu VI \quad (5)$$

Q—Effective heat energy (W);

μ —Weld efficiency;

V—Voltage (V);

I—Current (A).

The main parameters of the Goldak model were not fixed but varied depending on the welding conditions and the environment, and the appropriate values were obtained through a parametric study using a combination of several variables [10–14]. Lee estimated the main parameters of the Goldak heat source model by observing the cross-section after welding tests [10], Tchoumi used a symmetric source model to analyze the heat source for TIG welding using stainless steel 316L and applied the response surface minimization method to derive the parameters based on factorial DOE (Design of Experiments) results [11]. Chujutalli used FEM (Finite Element Method) to find the Goldak model's parameters by setting the peak temperature as the target and derived the values through a parametric study [12]. Podder estimated the main parameters by observing the cross-section after welding tests [13]. In addition to arc welding, studies are also conducted on estimating the heat source shape for analyzing thermal deformation in laser welding, and Kim performed a study to estimate the parameters by assuming the keyhole as a Gaussian distribution [14].

The Goldak model has at least four variables (a_f , a_r , b , and c), and if each variable is composed of five candidates, 625 combinations are configured, which is inefficient.

This study performed a more efficient parametric study by using a global optimization method instead of a full factorial method, which was widely used in the past. Adaptive simulated annealing and genetic optimization algorithm are the most well-known global optimization methods, and this study used the Multi-Island Genetic Optimization Algorithm (MIGA), which is a verified method widely used in welding and other research areas [15–18].

Hu used MIGA for the optimal design of satellite separation systems [15], and Lin used MIGA as a way to optimize energy efficiency in building design [16]. Wang used MIGA as a method to predict the lifetime of lithium-ion batteries [17], and Zhao used it to optimize the design of aircraft airfoils [18].

This study implemented simulations conducting BOP (Bead on Plate) tests on mild steel, using Abaqus (Dassault Systems) as the FEM software for the simulations and Fortran to implement the moving heat source. The performance of the software above has been verified and is widely used in research using welding simulations [19–22].

Isight (Dassault Systems), which is widely used to analyze various structures, was used to implement the genetic optimization algorithm [23–25]. Wang used Isight to optimize the design of compressor rotors [23], and Hahn used it for the optimal design of turbine blades [24].

The target of optimization was to match the HAZ (Heat Affected Zone) of the experiment with FEM. To achieve this, the HAZ was defined as the section that exceeds 727 °C during the welding process, and the HAZ line was coordinated and used for FEM analysis [26].

This study set the parameters of the Goldak heat source model, weld efficiency, and the location of the heat source as the variables, and identified the parameters when reaching the target values. Although previous studies fixed the heat source point on top of the bead [12,27], the concentration of the heat source occurs in the welding wire in actual welding. Per this configuration, it is difficult to represent the actual phenomenon by fixing the heat source point to the top of the bead in FEM modeling. Therefore, this study defined the heat source point as a variable, which is defined as shown in Figure 2.

Figure 2. Definition of the heat source point.

2. Background

2.1. Heat Source Model

This study applied the Goldak model, which is the most commonly used double-ellipsoidal heat source model. The Goldak model is recognized for its high consistency and has been applied to a wide variety of arc welding simulation research, such as SMAW, FCAW, SAW, Plasma Arc Welding (PAW), and GMAW [9–15].

2.2. Global Optimization Algorithm

A genetic algorithm is an optimization algorithm that simulates natural selection and the genetic process of living organisms. Most species select and cross genes that adapt well to a given environment to pass on superior genes to the next generation, and sometimes, mutation is used to pass on superior genes to later generations. This evolution continues through generations, leaving only the superior genes. A genetic algorithm is an optimization algorithm simulating this process, which can be applied to all optimization problems and is also effective in global optimization [28].

Figure 3 shows the flow of a genetic algorithm, where the process of initial population generation-selection-crossover-mutation-acceptance of the new generation-replacement of the new generation is repeated. Individuals are variables for optimization, and a solution is found by using a combination of individuals. New combinations are created based on the results of various combinations, in which new combinations are formed through crossover and mutation. Additionally, this solution is compared with the previous solution and is either adopted if there are improvements or is rejected if there are no improvements. The process continues through generations, and the population evolves until they find the target solution.

Figure 3. Genetic algorithm flow [15].

This study applied a multi-island genetic algorithm, which is an improved genetic algorithm. A multi-island genetic algorithm divides each population of individuals into several sub-groups called islands. The major difference is that conventional genetic algorithms are carried out in one group without sub-groups. In a multi-island genetic algorithm, all genetic operations are performed separately on each island, and migration occurs periodically from one generation to another. Figure 4 below shows the respective process.

Figure 4. Process of multi-island genetic algorithm flow [15].

Genetic algorithms are widely used for design optimization in the aviation and electronics industries, and are also used in some areas of research related to welding [15–18].

3. Experiment

3.1. Experiment Setup

This study used SS400 plates (200 mm × 80 mm × 15.6 mm) as the base metal to confirm the BOP. The same material with a diameter of 1.2 mm was used as the filler metal, and surface treatment was performed with a stainless wire brush and sand paper (#300) to ensure high welding quality. Tables 1 and 2 below show the properties and the chemical composition of the welding materials.

Table 1. Mechanical properties of the base metal and filler metal used.

Type	Material	TS (MPa)	YS (MPa)	Elongation (%)	Hardness (HV)
Base metal	SS400	435	325	25	128
Filler metal	AWS A5.29	550	470	19	-

Table 2. Chemical composition of the base metal and filler metal used.

Material	Composition (%)			
	C	Si	Mn	P
SS400	0.15	0.05	0.697	0.113
	S	Cu	Cr	Ni
	0.007	0.041	0.087	0.503
	C	Si	Mn	P
AWS A5.29	0.03	0.47	1.41	0.007
	S	Cu	Cr	Ni
	0.005	-	0.02	1.4

As shown in Figure 5, a welding system with a robot (Samsung, Suwon, Korea) was used for the experiment, by using the backhand welding technique and applying CO₂ as the shielding gas [29].

Figure 5. Welding system for the experiment.

3.2. Experiment Condition

The main welding conditions were: current (200 A), voltage (24 V), and shielding gas flow rate (18 ℓ/min). The CTWD (Contact Tip to Work Distance) was 21 mm and the wire feeding rate was fixed to 10 CPM (Centimeter Per Minute; Table 3).

Table 3. Welding parameters.

Parameter	Value	Parameter	Value
Current	200 A	Shielding gas flow rate	18 ℓ/min
Voltage	24 V	Welding speed	100 mm/min
Wire Feeding rate	100 mm/min		

3.3. Experiment Result and Data Measurement

After the welding experiment, the center of the specimen was cut to a size of 40 mm $\times$ 20 mm with a wire cutting machine to observe the dimensions of the HAZ. Polishing was performed using 3% HNO_3 and H_2O Nital solution, and an optical microscope system was used for a precise measurement. Based on the image, the required data were extracted by coordinating the bead size and the boundary of the HAZ as shown in Figure 6 and Table 4. The bead size was measured to be $W = 15.02$ mm, $H = 4.96$ mm.

Figure 6. Weld bead and Heat Affected Zone (HAZ) geometry.

Table 4. HAZ boundary coordinates.

HAZ Boundary	X-coordinate	Y-coordinate	HAZ Boundary	X-coordinate	Y-coordinate
Point 1	−9.0	0.0	Point 12	0.1	−6.5
Point 2	−8.8	−0.9	Point 13	1.4	−6.5
Point 3	−8.4	−1.7	Point 14	2.5	−6.0
Point 4	−8.1	−2.5	Point 15	3.7	−5.5
Point 5	−7.6	−3.3	Point 16	4.6	−5.1
Point 6	−6.8	−4.0	Point 17	5.6	−4.6
Point 7	−6.0	−4.9	Point 18	6.6	−3.9
Point 8	−4.8	−5.4	Point 19	7.3	−3.3
Point 9	−3.9	−6.0	Point 20	8.0	−2.0
Point 10	−3.0	−6.2	Point 21	8.4	−1.1
Point 11	−1.1	−6.6	Point 22	8.7	−0.2

4. Numerical Simulation

4.1. FE Simulation

This study used Abaqus (Ver. 2020, Dassault Systems Simulia Corp, RI, USA) as the FE software and a user subroutine function in Fortran (Ver.17.0, Intel, CA, USA) to simulate the moving heat source. Abaqus and Fortran are used in various studies because their performance has been verified in simulating and analyzing moving heat sources in welding.

The modeling process was performed under the same conditions as the actual experiment, and the bead shape was modeled by referring to the bead shape in the experiment as shown in Figure 7. Figure 8 shows the material properties of the base metal and the bead, which were derived by using JMatPro.

Figure 7. Modeling for FEM analysis applying a moving heat source.

Figure 8. Material property of SS400 by temperature.

A transient model was used to check the temperature change over time, simulating the heat source moving at a speed of 10 CPM (1.667 mm/s) in the Z-direction, which is the same condition as the actual experiment. For a quick analysis, a different mesh size was applied to each area to configure a 3D model composed of a total of 90,000 elements and 100,000 nodes. The 8-node linear heat transfer brick (DC3D8) element was used for this research, the minimum size of the element was 0.8 mm.

The cross-section in the Z-direction was confirmed by analyzing the results, which was 33.333 mm away from the initial point (20 s after welding). Since the heat source moved at a constant speed, the temperature distribution in each thickness direction was the same with a difference in time after 16.667 mm (Figure 9). In this welding condition, the edge effect did not have an affect after 16.667 mm.

Figure 9. Temperature distribution in the cross-section (under the heat source).

A moving heat source using the Goldak model was applied as the loading condition, and the film coefficients by temperature as the boundary conditions. Equation (6), Equation (7), and Figure 10 show the details of the boundary conditions. The film coefficients were applied to reflect both convective and radiant heat transfer by referring to a related study [12].

$$H = 0.0668 \times T \quad (T < 500) \quad (6)$$

$$H = (T \times 0.237) - 82.1 \quad (T > 500) \quad (7)$$

H—Film coefficient (W/m²K);

T—Temperature (°C).

Figure 10. Temperature-dependent film coefficient.

4.2. Target and Variables

The HAZ temperature was set as the target to determine the Goldak heat source model, which is the main purpose of this study. Figure 11 shows the results of simulating the HAZ border line of the experimental results, where the temperatures of the five check points were examined on each of the inner line and outer line offset 1 mm from the HAZ border line. The points on the inner check line should have a temperature distribution of 727 °C or higher during the welding process, and the points on the outer check line a temperature distribution of 727 °C or lower. The above criteria were set as the target.

Figure 11. HAZ border line and temperature check line.

A total of six variables were selected to achieve the target including the main variables of the Goldak model (a_f , a_r/a_f , b , c), weld efficiency, and the location of the heat source point.

Most previous studies fixed the relationship between a_r and a_f , which varied between the range of 3–5 depending on each study [18,30–32]. This study, however, sets this relationship as a variable

Table 5 defines the range of the main variables, which were defined as widely as possible to find the appropriate values.

Table 5. Variables and range.

Variables	Lower Bound	Upper Bound
a_f	1.0 mm	6.0 mm
a_r/a_f	2.0	7.0
b	1.0 mm	10.0 mm
c	1.0 mm	8.0 mm
μ (weld efficiency)	0.2	0.9
Distance to heat source	0 mm	4.96 mm

4.3. Algorithm Property

Table 6 shows the main parameters and details to apply the multi-island genetic algorithm.

Table 6. Parameters of multi-island genetic algorithm.

Parameter	Value	Note
Sub-population size	10	Population by island
Number of islands	10	Number of islands
Number of generations	10	Total number of evolved generations
Rate of crossover	100%	Crossover rate
Rate of mutation	1%	Mutation rate
Rate of migration	1%	Island migration rate
Interval of migration	5	Number of island migration generations

5. Results and Discussion

Over 1000 models were compared by using the optimal algorithm to find acceptable results. Table 7 shows the list of candidate groups created by the optimal algorithm that meets the conditions wherein the outer line was higher than 727 °C and the inner line was lower than 727 °C.

Table 7. Optimal value candidates created by the optimal algorithm.

Candidate	μ	a_f	b	c	Distance to Heat Source (mm)	a_r/a_f
1	0.47	1.90	4.02	4.72	4.47	2.41
2	0.46	1.90	4.02	4.72	4.43	2.41
3	0.47	1.90	4.01	5.96	4.19	2.41
4	0.42	1.28	3.82	5.79	3.66	6.83
5	0.47	1.90	4.02	4.72	4.43	2.84
6	0.32	3.68	5.25	3.70	1.82	2.10
7	0.47	1.90	4.02	4.72	4.43	6.59
8	0.59	5.81	5.96	4.13	0.18	5.09
9	0.32	3.21	5.25	3.70	1.82	2.10
10	0.32	3.21	5.25	3.70	1.79	2.10

After checking the temperature distribution results of each of the candidate groups above, this study selected the model with a HAZ boundary shape most similar to the actual experimental results. Based on the depth and width of the HAZ boundary, candidate groups similar to the experimental results were searched, and the temperature distribution was checked based on the time when each point reached its maximum temperature. For example, in the case of candidate group 1, the maximum length in the width direction occurred 31 s after welding (11 s after the heat source), the maximum length in the depth direction occurred 34 s after welding (14 s after the heat source), and the width after 31 s was 17.5 mm, and the depth after 34 s was 6.6 mm. Figure 12 shows the details, Table 8 shows the variables selected through this process, Table 9 shows the HAZ boundary derived from finite element analysis and the actual experimental values, and Table 10 shows the temperature of the check point. The check points are described in Figure 10.

Figure 12. Temperature distribution of FEM.

Table 8. Results of optimization.

Variables	Values
a_f	1.9 mm
a_r/a_f	2.41
b	4.02 mm
c	4.72 mm
μ (weld efficiency)	0.47
Distance to heat source	4.47 mm (Bead height = 4.96 mm)

Table 9. Dimension of HAZ.

Dimension of HAZ	Experiment	Result of FEM
Width	17.7 mm	17.5 mm
Depth	6.6 mm	6.6 mm

Table 10. Analysis results by measurement location.

Point	Value (°C)	Target value (°C)
Point 1 (P1)	754.7	>727
Point 2 (P2)	733.8	>727
Point 3 (P3)	768.6	>727
Point 4 (P4)	733.8	>727
Point 5 (P5)	754.7	>727
Point 6 (P6)	651.4	<727
Point 7 (P7)	662.2	<727
Point 8 (P8)	705.9	<727
Point 9 (P9)	662.2	<727
Point 10 (P10)	651.4	<727

Figure 13 shows the temperature distribution according to the time under the optimal conditions, where all of the points reached maximum temperature 30–34 s after welding (10–14 s after the source point; Table 11). This is because of the time required for heat conduction.

Figure 13. Temperature change over the time on check points.

Table 11. Temperature change over the time on check points (°C).

Time(s)	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
					...					
28	740.30	709.25	720.79	709.25	740.30	614.83	607.82	635.52	607.82	614.83
29	751.10	724.31	741.45	724.31	751.10	630.50	627.36	659.08	627.36	630.50
30	756.30	733.84	756.19	733.84	756.30	641.61	642.23	677.54	642.23	641.61
31	756.18	738.21	765.67	738.21	756.18	648.54	652.83	691.60	652.83	648.54
32	752.68	738.70	770.17	738.70	752.68	652.23	659.84	701.39	659.84	652.23
33	745.70	735.63	770.37	735.63	745.70	652.86	663.58	707.34	663.58	652.86
34	735.68	729.40	767.22	729.40	735.68	650.67	664.32	710.03	664.32	650.67
35	723.51	720.31	760.57	720.31	723.51	645.99	662.26	709.53	662.26	645.99
36	709.21	708.63	750.92	708.63	709.21	638.99	657.59	706.11	657.59	638.99
37	693.07	694.96	739.29	694.96	693.07	630.01	650.70	700.34	650.70	630.01
38	676.73	680.67	726.85	680.67	676.73	620.09	642.38	692.99	642.38	620.09
					...					

This study examined the main parameters of the Goldak model, weld efficiency, and the location of the heat source. The results showed that the location of the heat source in the Y-direction should be placed on top of the bead as in the case of previous studies, and the b and c values were also confirmed to be similar.

Finding the main parameters of the welding heat source should be a prerequisite in analyzing temperature distribution due to heat transfer and thermal deformations. This study applied a multi-island genetic algorithm (global optimization algorithm) to achieve this purpose and derived significant results.

6. Conclusions

This study used a multi-island genetic algorithm (optimization algorithm) to find the parameters of the Goldak heat source model (a welding heat source model), weld efficiency, and the location of the heat source.

1. The temperature distribution was confirmed by the finite element analysis using a moving heat source by simulating a BOP (Bead on Plate) test with SS400 plates.
2. The HAZ boundary of the specimen was coordinated, and the target was determined by analyzing the results at the line offset from the HAZ boundary. The target was set so that the temperature distribution of the inner offset line is 727 °C or higher and the outer offset line is 727 °C or lower.
3. The optimal results were derived by using Isight's multi-island algorithm. These results were derived by comparing over 1000 candidate groups by performing non-linear optimization using global optimization techniques.
4. Based on the results of global optimization, the HAZ boundary line was derived through finite element analysis, and was similar to the actual experimental results.
5. Applying a search method using a multi-island algorithm was found to be useful in finding the welding heat source parameters required for welding heat transfer/thermal deformation analysis.

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