UDC 539.4

Application of Taguchi Approach to Optimize Laser-Arc Hybrid Welding Parameters of Galvanized Steel

HanSur Bang,[a] HeeSeon Bang,[a,1] M.-J. Na,[b] G.-H. Jeon,[b] G.-S. Kim,[b] and B.-R. Kim[b]

[a] Department of Welding and Joining Science Engineering, Chosun University, Gwangju, Republic of Korea

[b] Department of Welding and Joining Science Engineering, Graduate School, Chosun University, Gwangju, Republic of Korea

[1] banghs@chosun.ac.kr

This study aims to establish the weld quality of the Nd:YAG laser-MIG hybrid welding on galvanized steel (SGACC60). In order to do so, the Taguchi analysis optimized the laser-arc hybrid welding process for SGACC60 by varying four parameters: welding speed, welding current, laser-arc distance and shielding gas. The experiment produced 18 combinations of these four essential welding parameters, which were estimated in terms of ultimate tensile strength, welding depth and width ratio, and hardness. The optimum result exhibited that the tensile strength of welds was approximately 101% of that of the base metal, and that their hardness was within the acceptable range (the maximum value 350 Hv).

Keywords: Nd:YAG laser-MIG hybrid, Taguchi analysis, galvanized steel, ultimate tensile strength, welding depth and width ratio, hardness.

Introduction. Due to many advantages, such as high welding speed, small heat-affected zone (HAZ), low cost and high strength, laser-arc hybrid welding techniques are regarded very promising among manufacturing industries [1, 2]. For instance, hybrid welding is much more tolerant to joint fit-up variations than laser welding, since it is able to maintain deep penetration [3]. While many researchers have investigated the influence of energy parameters (laser power, arc voltage, arc current) [4, 5] and distance (laser-arc distance, laser beam focal position) [6, 7], some have used the Taguchi method to optimize welding parameters [8, 9] as it is widely adopted for solving optimization problems in the field of manufacturing process. Taguchi method utilizes orthogonal array design, a well-balanced experimental design, and signal-to-noise ratio (S/N ratio), whose objective is to optimize its experimental domain [10–17].

Thus, this study intends to optimize the laser-arc hybrid welding parameters of galvanized material (SGACC60), which has a broad field of application in the manufacturing process.

1. **Experimental Design and Procedure**.

1.1. ***Experimental Details***. In this study, galvanized steel (SGACC60) sheets ($L\times B\times t = 150\times 75\times 0.65$ mm) were used in butt welding. The laser power source used in the experiment was a continuous wave Nd:YAG laser with maximum output power of 3 kW. Along with a remote wire feed unit and a straight type torch, MIG welding was used in hybrid welding. Figure 1 shows the Nd:YAG laser-MIG hybrid welding system.

The experiment for hybrid welding used a MIG wire (KC-28, 0.8 mm diameter). Tables 1 and 2 illustrate the chemical composition of materials, solid wire and the mechanical properties of the material, respectively.

Using the Taguchi analysis, the hybrid welding process for galvanized material was optimized by varying four parameters: welding speed, welding current, laser-arc distance, and shielding gas. The evaluation indices for the weld in this study were reinforcement, T a b l e 1

Chemical Composition of Material SGACC60 and Solid Wire KC-28

Material	Chemical composition (wt.%)					
	C	Si	Mn	P	S	S-Al
SGACC60	0.0013	0.003	0.01	0.01	0.005	0.05
KC-28	0.08	0.5	1.05	0.014	0.01	–

T a b l e 2

Mechanical Properties of SGACC60

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
SGACC60	152.0	299.1	45.0

Fig. 1. Nd:YAG laser-MIG hybrid welding system.

under cut, excess weld metal and excessive penetration of weld bead. Furthermore, the effect of welding process variables based on the welding defect standard (EN ISO 13919-1) for electron beam and laser welding [9] determined the welding conditions.

1.2. ***Hybrid Welding Process via Taguchi Analysis***. Welding conditions were selected for the BOP (bead on plate) conducting test. The initial values of the welding parameters were welding speed at 2.6 m/min, welding current at 120 A, laser-arc distance at 4 mm and shielding gas at 90%Ar+10%CO_2. In order to determine the optimal welding parameters, the welding experiments set the welding speed at 2.6 and 2.8 m/min, welding current at 110, 120, and 130 A, laser-arc distance at 2, 4, and 6 mm, and shielding gas at 85%Ar+15%CO_2, 90%Ar+10%CO_2, and 95%Ar+5%CO_2. Table 3 shows the summary of experimental conditions. The experimental results after welding are evaluated in views of ultimate tensile strength (UTS), depth/width (D/W), and hardness.

To achieve superior weldability, Taguchi's experimental design and $L_{18}[2^1 \times 3^3]$ orthogonal array is adopted for conducting experiments.

1.2.1. ***Orthogonal Arrays***. Taguchi method determined the dominating factors incorporated in the optimization of hybrid welding. The welding process considered the four welding parameters (welding speed, welding current, laser-arc distance, and shielding gas) at two or three different levels, respectively. Experimental layout using $L_{18}[2^1 \times 3^3]$ and results are summarized in Table 4.

Table 3

Welding Parameters and Their Levels

Factor	Parameter	Level 1	Level 2	Level 3
A	Welding speed (m/min)	2.6* (A_1)	2.8 (A_2)	–
B	Welding current (A)	110 (B_1)	120* (B_2)	130 (B_3)
C	Laser-arc distance (mm)	2 (C_1)	4* (C_2)	6 (C_3)
D	Shielding gas	85%Ar+15%CO_2 (D_1)	90%Ar+10%CO_2 (D_2)*	95%Ar+5%CO_2 (D_3)

* Initial process parameters.

Table 4

Experimental Layout and Results

Group No.	Factor A (m/min)	Factor B (A)	Factor C (mm)	Factor D	UTS (MPa)	D/W	Hardness (Hv)
1	2.6	110	2	1	247	0.708	209.2
2	2.6	110	4	2	254	0.762	211.4
3	2.6	110	6	3	260	0.765	214.2
4	2.6	120	2	1	273	0.785	217.5
5	2.6	120	4	2	279	0.787	220.3
6	2.6	120	6	3	283	0.791	224.2
7	2.6	130	2	1	293	0.803	228.2
8	2.6	130	4	3	302	0.813	239.0
9	2.6	130	6	1	287	0.801	227.5
10	2.8	110	2	3	242	0.732	208.4
11	2.8	110	4	1	257	0.693	209.2
12	2.8	110	6	2	227	0.543	201.2
13	2.8	120	2	2	263	0.762	210.3
14	2.8	120	4	3	268	0.761	209.8
15	2.8	120	6	1	251	0.758	207.3
16	2.8	130	2	3	265	0.760	208.6
17	2.8	130	4	1	276	0.763	213.7
18	2.8	130	6	2	263	0.753	208.3

Orthogonal array provides a set of well-balanced (minimum experimental runs) experiments and Taguchi's signal-to-noise ratio (S/N), which are logarithmic functions of desired output that serve as functions for optimization. This technique helps in data analysis, as well as in predicting optimum results. In order to evaluate the optimal parameter setting, Taguchi method uses a statistical measure of performance called signal–to-noise ratio. The S/N ratio is the ratio of the mean and the variability taken into account. The quality characteristics of the optimized [10] process determine the ratio.

2. **Analysis and Discussion**.

2.1. ***Hybrid Welding Parameters Analysis via the Taguchi Method***. The data sequences had a characteristic of H.B (the-higher-the-better). The values of UTS, D/W, and hardness applied to the Taguchi analysis were obtained from Table 5, which sets the hybrid welding parameters value in the design of the experiment. From the results, it was found that A_1, B_3, C_2, and D_3 showed the highest value of response for factors A, B, C and D, which indicate the optimal welding parameter combination of the hybrid welding process. When the last column of Table 5 is compared, it was observed that the delta Δ_i for welding current is the highest. This suggests that the welding current has a greater influence on multi-performance characteristics. Figure 2 shows the S/N ratio of the four welding parameters. Since in this study the parameters that supplied the largest average response were selected, it was optimized using welding speed at 2.6 m/min, welding current at 130 A, laser-arc distance at 4 mm, and shielding gas at 95%Ar+5%CO_2.

T a b l e 5

Response Table for All Factors

Parameter	Level 1	Level 2	Level 3	Δ_i	Rank
Welding speed (m/min)	165.8*	155.3	–	10.5	2
Welding current (A)	152.5	161.7	167.4*	14.9	1
Laser-arc distance (mm)	159.4	163.6*	158.6	4.9	3
Shielding gas	160.0	158.9	162.7*	3.8	4

* Optimal level.

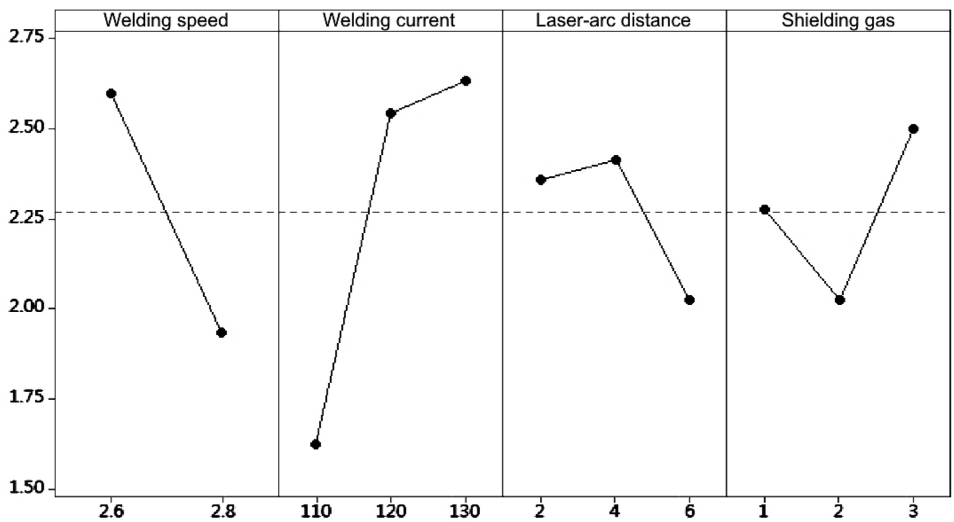

Fig. 2. Main effect plot for S/N ratio.

2.2. ***Confirmation Test***. Since the optimal level of the process parameters has been selected, the final step is to validate the enhancement of the performance using the optimal setting of the process parameters. To validate the results, three confirmation experiments were carried out at the optimal settings of process parameters.

Table 6 compares the experimental results obtained using the initial and optimal welding process parameters. According to Table 6, UTS increased from 279 to 302 MPa, while D/W increased from 0.787 to 0.813, and hardness increased from 220.3 to 239 Hv. In

T a b l e 6

Results of Welding Performance Using the Initial and Optimal Welding Process Parameters

Parameters	Initial process parameters	Optimal process parameters
Level	A_1 B_2 C_2 D_2	A_1 B_3 C_2 D_3
UTS (MPa)	279	302
D/W	0.787	0.813
Hardness (Hv)	220.3	239.0

T a b l e 7

Optimized Hybrid Welding Conditions

Welding condition		Value
Welding speed (m/min)		2.6
Laser-arc distance (mm)		4
Gap size (mm)		0
Shielding gas		95%Ar+5%CO_2
Laser	Peak power (kW)	3
	Defocusing length (mm)	223
MIG	Voltage (V)	12
	Current (A)	130
	C.T.W.D (mm)	20
	Torch angle (deg)	30

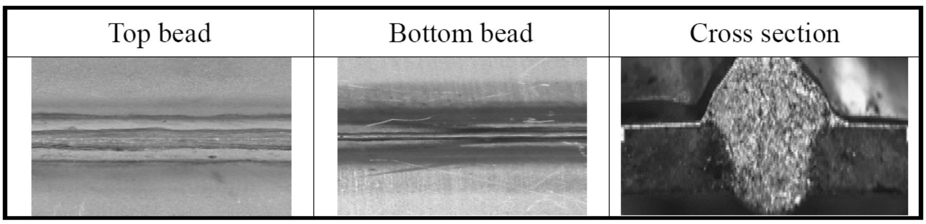

Fig. 3. Bead profiles of hybrid butt welded joints.

laser-arc hybrid welding, satisfactory D/W and mechanical properties (UTS, hardness) of welds can be achieved with varying welding parameters (welding speed, welding current, laser-arc distance) related to heat input. The laser-arc distance is one of the key parameters, which directly affects the distribution energy density, bead shape and undercut. From the results, it was found that lower welding speed, higher welding current and certain laser-arc distance improved D/W and UTS. At laser-arc distance of 4 mm, the penetration depth was the deepest. On the other hand, at laser-arc distance over 6mm, it became shallow. It indicates the effectiveness of interaction between laser and arc is reduced and the penetration depth is decreased. Figure 3 shows bead profiles of hybrid welded joints fabricated under optimal welding process parameters. The welds show a well balanced bead cross section with sufficient reinforcement and controlled excessive back bead. Moreover, defects such as undercut and porosity are not formed in the microstructure. Therefore, in quality level for weld imperfection based on EN ISO 13919-1, the optimized hybrid welding process parameters of the welded joints can be classified as very stringent (Quality B’). Three tensile specimens are cut out perpendicular to the welding line from welded test plate. All specimens for the tensile test failed in base metal (BM). Tensile strength of hybrid welded joints is about 302 MPa. Hardness values at distance of 0.3 mm from the top surface of hybrid welded joints are in the order of WM > HAZ > BM (WM – weld metal) due to rapid heating and cooling effect of laser welding. The hardness of hybrid welded joints exhibits within the acceptable range (the maximum value 340–360 Hv).

2.3. ***Optimization of Hybrid Welding Process***. Taguchi analysis optimizes hybrid welding parameters such as welding speed, welding current, laser-arc distance, and shielding gas. Ultimately, it finds out that the performance characteristics of hybrid welding parameters were enhanced. The optimum hybrid welding process conditions are shown in Table 7.

Conclusions

1. The welding current is the most significant parameter that has an influence on multi-performance characteristics of ultimate tensile strength (UTS), welding depth and width ratio (D/W), and hardness.

2. The conditions of the optimized hybrid welding parameters were as follows: welding speed at 2.6 m/min, welding current at 130 A, laser-arc distance at 4 mm, and shielding gas at 95%Ar+5%CO_2.

3. For weld imperfection such as reinforcement, undercut, excess weld metal and excessive penetration based on EN ISO 13919-1, the quality level of the optimized hybrid welding process parameters of the welded joints is classified as very stringent (Quality B’).

Acknowledgments. This study was supported by research fund from Chosun University, 2013.

1. Q. A. Wu, J. K. Gong, G. Y. Chen, and L. Y. Xu, “Research on laser welding of vehicle body,” *Opt. Laser Technol.*, **40**, 420–426 (2008).
2. E. Beyer, U. Dilthey, R. Imhoff, et al., “New aspects in laser welding with an increased efficiency,” in: Proc. of ICALEO’94, Orlando, FL (1994), pp. 183–192.
3. S.-M. Joo, H.-S. Bang, and S.-Y. Kwak, “Optimization of hybrid CO2 laser-GMA welding parameters on dissimilar materials AH32/STS304L using Grey-based Taguchi analysis,” *Int. J. Prec. Eng. Manuf.*, **15**, 447–454 (2014).
4. C. Fuhrmann, D. Petring, and R. Poprawe, “Recent results on high power CO_2 and Nd:YAG laser-arc welding of thick steel plates,” in: Proc. of the 3rd Int. WLT Conf. on *Lasers in Manufacturing* (2005), pp. 185–192.
5. M. Katsuna and L. Chen, “Interaction of both plasmas in CO_2 laser-MAG hybrid welding of carbon steel,” in: Proc. of SPIE (2003), Vol. 4831, pp. 341–346.
6. S. Katayama, Y. Naito, S. Uchium, and M. Mizutani, “Penetration and porosity prevention mechanism in laser-arc hybrid welding,” in: Proc. of the 3rd Int. WLT Conf. on *Lasers in Manufacturing* (2005), pp. 193–198.
7. M. El Rayes, C. Walz, and G. Sepold, “The influence of various hybrid welding parameters on bead geometry,” *Suppl. Weld. J.*, 147-S–153-S (2004).
8. S. Herbert, “Laser-hybrid welding of ships,” *Weld. J.*, **83**, No. 6, 39–44 (2004).
9. L. K. Pan, C. C. Wang, S. S. Wei, and H. F. Sher, “Optimizing multiple quality characteristics via Taguchi method-based Grey analysis,” *J. Mater. Process. Technol.*, **182**, No. 1, 107–116 (2007).

10. Saurav Datta, Asish Bandyopadhyay, and Pradip Kumar Pal, "Grey-based Taguchi method for optimization of bead geometry in submerged arc bead-on-plate welding," *Int. J. Adv. Manuf. Technol.*, **39**, 1136–1143 (2008).

11. *Metals Handbook – Ninth Edition (Vol. 8 – Mechanical Testing)*, ASM Handbook Committee (1985).

12. S. Maghsoodloo, G. Ozdemir, V. Jordan, and C.-H. Huang, "Strengths and limitations of Taguchi's contributions to quality, manufacturing, and process engineering," *J. Manuf. Syst.*, **23**, No. 2, 73–126 (2004).

13. Amit Kumar Sinha, Duck Young Kim, Darek Ceglarek, "Correlation analysis of the variation of weld seam and tensile strength in laser welding of galvanized steel," *Opt. Lasers Eng.*, **51**, 1143–1152 (2013).

14. M. Khan, L. Romoli, M. Fiaschi, et al., "Experimental design approach to the process parameter optimization for laser welding of martensitic stainless steels in a constrained overlap configuration," *Opt. Laser Technol.*, **43**, 158–172 (2011).

15. D. Havrilla, "Photonics applied: materials processing-successful laser welding demands optimized laser joint design," *Laser Focus World*, **48**, 43–48 (2012).

16. P. Sathiya, M. Y. Abdul Jaleel, D. Katherasan, and B. Shanmugarajan, "Optimization of laser butt welding parameters with multiple performance characteristics," *Opt. Laser Technol.*, **43**, 660–673 (2011).

17. D. X. Yang, X. Y. Li, D. Y. He, et al., "Optimization of weld bead geometry in laser welding with filler wire process using Taguchi's approach," *Opt. Laser Technol.*, **44**, 2020–2025 (2012).

Received 03. 08. 2015