



Optimization of hybrid CO₂ laser-GMA welding parameters on dissimilar materials AH32/STS304L using Grey-based Taguchi analysis

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ABSTRACT

This study intended to verify the feasibility of laser-arc hybrid welding to dissimilar materials joints between high strength steel (AH32) and stainless steel (STS304L). For this, hybrid welding process for dissimilar materials was optimized by varying four parameters (welding speed, welding current, wire feeding rate, welding voltage) through Grey-based Taguchi analysis. A Grey relational analysis of the ultimate tensile strength (UTS), welding depth to width ratio (D/W) and absorbed energy (AE) attained from the Taguchi method can optimize the multiple-performance characteristics of the Grey relational grade. Moreover, hardness values and fatigue strength of welded joints fabricated under welding condition optimized by Grey-based Taguchi analysis were investigated. From the results, it was found that the initial visual test of the welds could be classified as very stringent (Quality B') in quality levels for weld imperfections based on EN ISO 13919-1. In the tensile test of welded joints, the damaged part was in BM of STS304L side. Tensile strength of welded joints in dissimilar materials was comparable to that of STS304L base material. Hardness values at distances of 3mm and 12mm over the bottom surface of welded joints were in the order of WM > HAZ > BM. The hardness of welded joints exhibits within the acceptable range (the maximum value 340Hv~360Hv). Dissimilar materials hybrid welded joints exhibited almost same fatigue strength for similar material STS304L SAW welded joints and lied well above the design curve(level D) for JSSC.

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Introduction

Steel structures can be made more functionally and economically with the fabrication of structural members using dissimilar materials. It is often desired to use dissimilar materials (high strength steel and stainless steel) to provide higher strength and performance to bridges, ships, offshore structures, and pipelines.

Laser-arc hybrid welding has been in spotlight recently as a revolutionary method in manufacturing industries due to its high welding speed, low distortion, deep penetration, high mechanical properties [1-2]. And the process is much more tolerant to joint fit-up variations than laser welding, maintaining its deep penetration. This enables the full penetration welds of thick plates, which eliminates multiple passes and reduces after welding work such as cutting for adjustment and fairing at the assemble stage [3-4]. The application of laser-arc hybrid welding to dissimilar materials between high strength steels and stainless steels offers substantial advantages to large structures [8-9] because it secures safety against catastrophes due to weld defects.

Therefore, this study intend to optimize laser-arc hybrid welding parameters with multiple performance characteristics to dissimilar materials joints between high strength steel (AH32) and stainless steel (STS304L).

For this, hybrid welding process in dissimilar materials was optimized via Grey-based Taguchi analysis [5-6] that has a broad field of application in manufacturing processes, which solve multi-objective optimization problem simultaneously.

Moreover, the analysis of variance(ANOVA) and confirmation test were conducted to clarify the experimental results.

Research Method

Experimental details

AH32 and STS304L plates (600mm(L)x 250mm(B)x 13mm(t)) were used for butt welding of dissimilar materials (AH32-ST304L) at zero gap conditions.

TRUMPF 12000 TLF turbo continuous wave 12KW CO₂ laser with 250m focal length (focus diameter 0.8m) was coupled with FRONIUS TPS 5000 MIG welding equipment for hybrid welding experiment. Shielding gas was supplied through a MIG torch located at the side of laser head. The arc leading laser-arc hybrid welding was implemented, where the laser beam was focused perpendicular on the surface of the specimen. Laser focal distance (250 mm) and contact tip to work distance (CTWD=20 mm) were kept constant throughout the welding process. The angle between the electrode and the welding direction is 45°. MIG wire (AWS A5.9 ER309L, 1.2 mm diameter) was used in the experiments for dissimilar materials welding. Table 1 and Table 2 show the chemical composition and mechanical properties of the base materials, respectively.

The hybrid welding process for dissimilar materials was optimized by varying process parameters through Grey-based Taguchi analysis. The hybrid welding process for dissimilar materials was optimized by varying four parameters (welding speed, welding current, wire feeding rate, welding voltage) in this study. Welding experiment is repeated three times under same condition.

Hybrid welding condition for dissimilar materials was made allowance for the hybrid welding conditions obtained from the butt welding of similar materials (AH32-AH32, STS304L-ST304L) that were determined by varying selected four parameters (shielding gas composition ratio, laser-arc distance, laser power) in previous study[10].

In this study, the reinforcement, back-bead, undercut and uniformity of weld bead were considered as the evaluation indices for welds and the welding conditions were determined by evaluating the effect of welding process variables based on the welding defect standard (EN ISO 13919-1) for electron beam and laser welding[11]. Hardness measurement and fatigue tests[12-14] of welded joints fabricated under welding condition optimized by Grey-based Taguchi analysis in section 3.2.(A) were carried out.

Hardness values at distances of 3mm and 12mm over the bottom surface of welded joints were carried out.

The fatigue tests for dissimilar materials AH32-ST304L hybrid welded joints were carried out under pulsating tensile loading with the stress ratio $R=(P_{min}/P_{max})=0.1$.

The dimensions of specimen were chosen according to the standard ASTM E466. The dimensions of the fatigue specimen are length of 140.5mm, width of 15mm and thickness of 3.0mm. The fatigue test specimen was selected in the transverse direction of welded specimen. The applied cyclic loading waveform was sinusoidal and the frequency of loading used was varied from 55 to 57Hz according to the load amplitude.

Optimization of welding process via Grey-based Taguchi analysis

Experimental procedure

Optimum welding process parameters, which considered the multiple performance characteristics, were acquired. The initial values of the welding parameters were welding speed of 1.3m/min, arc current of 300A, wire feeding rate of 9.8 m/min, and arc voltage of 28V. Welding experiments for determining the optimal welding parameters were carried out by setting the welding speed at 1.3 or 1.5m/min, arc current at 260 or 280 or 300A, wire feeding rate at 7.4 or 8.6 or 9.8m/min and arc voltage at 23 or 25 or 28V.

The summary of experimental conditions is shown in Table 3. The experimental results after hybrid welding were estimated in terms of the following measured performance: (1) ultimate tensile strength (UTS), (2) welding depth to width ratio (D/W) and (3) absorbed energy (AE). In order to attain supreme weldability, Taguchi's experimental design was utilized for conducting experiments. For this, a L_{18} orthogonal array was used for the experiment.

Table 3 Hybrid welding parameters and their levels (* Initial process parameters)

Factors	Parameter	Level1	Level 2	Level 3
A	Welding speed(m/min)	1.3*	1.5	-
B	Welding current(A)	260	280	300*
C	Wire feeding rate(m/min)	7.4	8.6	9.8*
D	Welding voltage(V)	23*	25	27

Determination of welding process parameters

The welding parameters were determined by the Grey-based Taguchi method.

Orthogonal arrays

Taguchi's method determined the domineering factors incorporated in the optimization for hybrid welding. In this welding process, the four welding parameters such as welding speed, welding current, wire feeding rate and welding voltage

were considered, at two or three different levels respectively. Among these four parameters, welding speed at two-levels were considered and the others (welding current, wire feeding rate and welding voltage) were considered at three-levels. Therefore, a total of $54(2 \times 3 \times 3 \times 3)$ different combinations were considered. According to Taguchi, however, the samples could be classified into 18 groups.

Table 4 illustrates the grouping of the samples into 18 groups according to Taguchi. The numbers indicate the various experimental arrangements or levels of the differing factors.

Table 4 Experiment layout using L_{18} orthogonal arrays

Group no.	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

In Table 5, the experimental results were summarized.

(B) Grey relational analysis

Grey analysis was used in evaluating the performance of a complicated design. Nevertheless, the data applied in Grey analysis was demanded to be pre-processed into quantitative indices to normalize raw data for analysis.

1) Data pre-processing

Data pre-processing is a process of assigning the original sequence to a comparable sequence. For this, the experimental raw results are normalized in the range between zero and one.

The three necessities such as ultimate tensile strength, welding depth to width ratio and absorbed energy in welded joints in this study correlate with the definition of "the-higher-the-better type". When the form "the-higher-the-better" becomes the anticipated value of the data sequence, the original sequence is normalized as follows.

$$x_i^*(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \tag{1}$$

However, if there is "a specific desired value", then original sequence can be normalized using this equation.

$$x_i^*(k) = 1 - \frac{|x_i^o(k) - x^o|}{\max (\max x_i^o(k) - x^o, x^o - \min x_i^o(k))} \tag{2}$$

where, $x_i^o(k)$ is the original sequence, $x_i^*(k)$ is a normalized value of kth element in the ith sequence, $\max x_i^o(k)$ is the largest value of $x_i^o(k)$, and $\min x_i^o(k)$ is the smallest value of $x_i^o(k)$, x^o is the desired value of the kth quality characteristics .

Grey relational coefficient and Grey relational grade

After data pre-processing is carried out, a grey relational coefficient can be computed to specify relation between the ideal and actual normalized experiment results. The grey relational coefficient can be defined as follows [5-6].

$$\xi_j(k) = \frac{\Delta_{\min} + \zeta \cdot \Delta_{\max}}{\Delta_{0j}(k) + \zeta \cdot \Delta_{\max}} \tag{3}$$

Where $\Delta_{oi}(k)$ is the absolute value of difference between $x_0^*(k)$ and $x_i^*(k)$

$$\Delta_{oi}(k) = \|x_0^*(k) - x_i^*(k)\| \tag{4}$$

$$\Delta_{\max} = \max_{vjei} \max_{vk} \|x_0^*(k) - x_j^*(k)\| \tag{5}$$

$$\Delta_{\min} = \min_{vjei} \min_{vk} \|x_0^*(k) - x_j^*(k)\| \tag{6}$$

ξ is identifying coefficient and $\xi = 0.5$ is generally used.

Generally, the average of the grey relational coefficient is taken as the grey relational grade after attaining the grey relational coefficient. The grey relational grade is represented as follows :

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \tag{7}$$

The grade γ_i suggests the correspondence between the reference sequence and the specific sequence x_i . Since the grade, γ_i , has been evaluated through considering three requirements, the highest grade among all 18 groups precisely signifies the optimized combination for hybrid welding.

Analysis and discussion

Experimental results

In this study, UTS (ultimate tensile strength), D/W (welding depth to width ratio) and AE (absorbed energy) under different welding parameters and experiments are shown in Tables 6. The data sequences had a the-higher-the-better characteristic. The values of UTS, D/W and AE were applied to the reference sequence $x_0^*(k)$ ($k = 1\sim 3$) The results of 18 experiments were the comparability sequence $x_i^*(k)$, ($i = 1,2,\dots,18, k = 1\sim 3$). Table 6 shows all sequences, which following data pre-processing using Eq. (1). Moreover, the deviation sequences $\Delta_{oi}(k)$, $\Delta_{\max}(k)$ and $\Delta_{\min}(k)$ for $i = 1\sim 18, k = 1\sim 3$ can be computed in Eq. (4)~(6).

Table 7 lists the Grey relational coefficient and grade for each case of the L_{18} orthogonal array by using Eq. (3) and (7). According to the designed layout of the experiment, it was obtained from Table 7 that the setting of the hybrid welding parameters values in experiment No.9 had the highest Grey relation grade, which offered the best multi-performance characteristics out of the 18 experiments.

In order to calculate the average grey relational grade for each factor level, the response of the Taguchi method was applied. The process categorized the relational grade primarily by the factor level for each column in the orthogonal array, and then averages them. Hence, the comparability sequence had a larger value of Grey relational grade for the UTS, D/W and AE. Derived from this assumption, this study selected the level that supplied the largest average response.

In Table 8, A1, B3, C3 and D3 illustrate the largest value of Grey relational grade for factors A, B, C and D respectively, which suggest the optimal parameter combination of the hybrid welding process.

The Grey relational grade graph in Fig. 1 demonstrated the change in the response, when the factors are varied for their level 1- level 2 or level 3. This figure, the greater values gave the high UTS, D/W and AE. When the last column of Table 8 was compared, it was observed that the difference between the maximum and the minimum value of the Grey relational grade for factor B was the greatest. This suggests that the welding current has a stronger influence on the multi-performance characteristics.

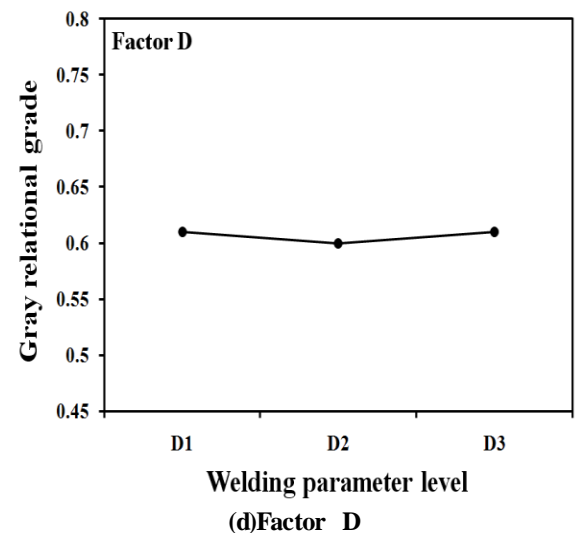
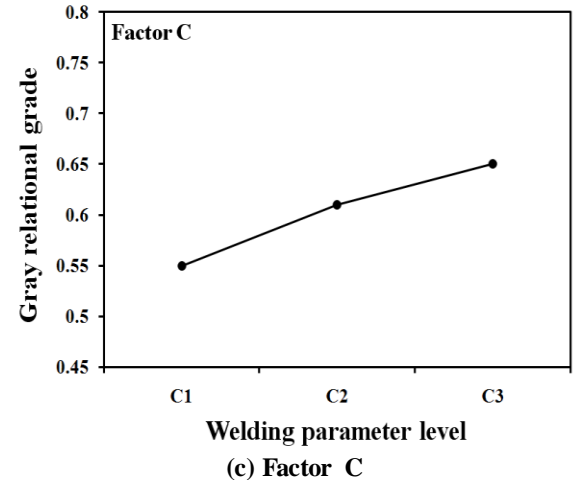
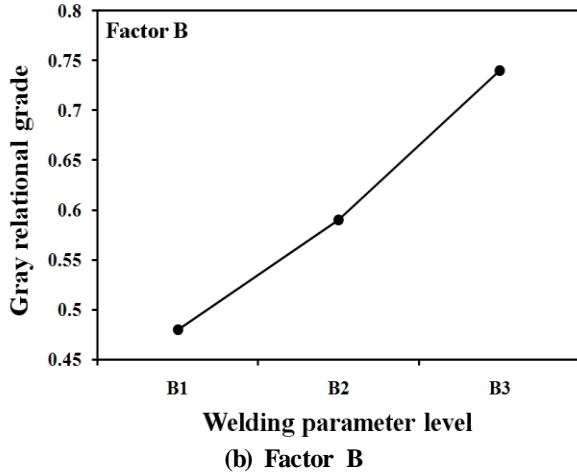
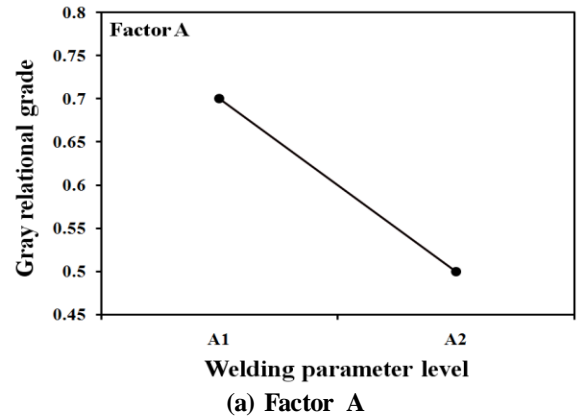


Fig. 1 Graph of grey relational grade

Confirmation test

The final step is to validate the improvement of the performance characteristics by using the optimum levels of the welding process parameters. Table 9 shows the comparison of experimental results attained using the initial and optimal welding process parameters. As shown in Table 9, UTS was increased from 502 to 508, D/W was increased from 1.948 to 1.959, and AE was increased from 202 to 207.

Development of welding process

Grey relational analysis

A Grey relational analysis of the UTS, D/W and AE attained from the Taguchi method can optimize the multiple-performance characteristics of the Grey relational grade. Conclusively, it was found that the performance characteristics of the hybrid welding process such as UTS, D/W and AE are enhanced.

Details on welding condition are given in Table 10. Cross section of butt welded joints is shown in Fig. 2.

The bead width and reinforcement are 9mm and 2mm, respectively, and the bead width of AH32 side was about 1mm greater than that of STS304L mainly due to the thermal conductivity difference between the two base metals, that is, the thermal conductivity of AH32 is higher than that of STS304L. Back bead width and height were 1mm and 0.3mm, respectively, and the welded joints showed a well balanced bead cross section with sufficient reinforcement and controlled excessive back bead.

Moreover, defects such as undercut and porosity was not formed in the microstructure; therefore, the initial visual test of the welds could be classified as very stringent (Quality B) in quality levels for weld imperfections based on EN ISO 13919-1.

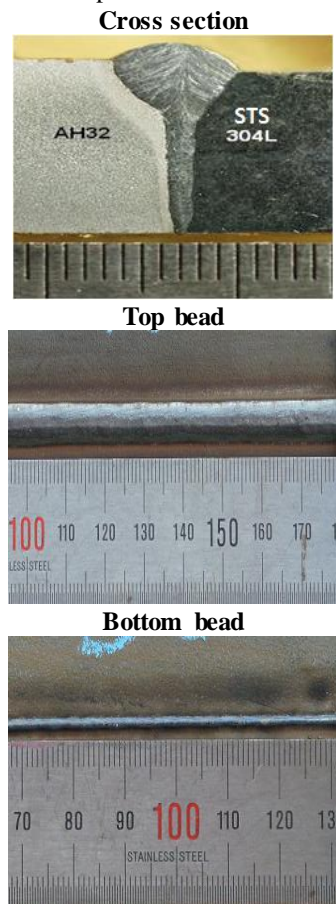


Fig. 2 Bead surface appearance and cross section of AH32-ST304L hybrid butt welded joints

Hardness

Hardness measurement of welded joints fabricated under welding condition optimized by Grey-based Taguchi analysis in section 3.2.(A) was carried out. Measured values at distances of 3mm and 12mm over the bottom surface of welded joints are shown in Fig. 3.

From the result shown in Fig. 3, it was found that the hardness values at distances of 3mm and 12mm over the bottom surface of hybrid welds were in the order of WM > HAZ > BM. The hardness at distance of 3mm over the bottom surface was higher than that at distance of 12mm over bottom surface, whose lower part was affected mainly by rapid heating and cooling characteristics of laser process.

In addition, the hardness of WM in AH32 was higher than that of STS304L due to the much more rapid heating and cooling rate. Difference between the hardness value in HAZ and that in BM is not so large at $y=12\text{mm}$; however, at $y=3\text{mm}$, away from the bottom surface, the hardness in HAZ was significantly higher than that of BM.

Comparing the hardness value of WM and BM at distance of 3mm over the bottom surface, general hardness values of STS304L and AH32 used in experiment were approximately 195Hv and 182Hv; however, the maximum hardness values of WM were 297Hv and 348Hv.

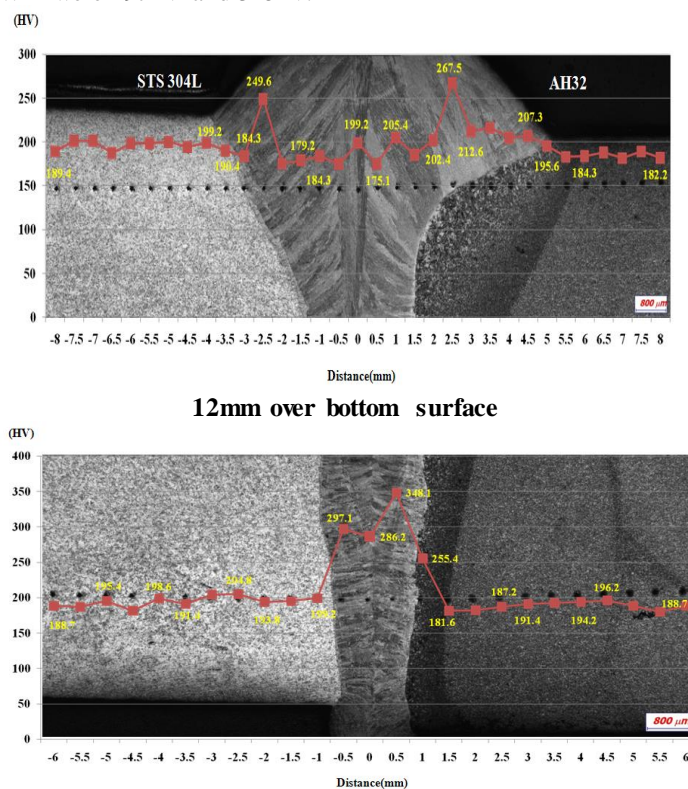


Fig. 3. Distribution of hardness in dissimilar materials hybrid welded joints

Fatigue strength

Fatigue strength of welded joints fabricated under welding condition optimized by Grey-based Taguchi analysis in section 3.2.(A) were investigated. The fatigue strength is determined in the life range 10^4 - 10^7 cycles. Fatigue life is defined as the cycle number during which a specimen is divided into two parts, and the fatigue limit is considered to be 10^7 cycles.

Figure 4 represents the S-N diagrams of the dissimilar materials hybrid welded joints compared with that of similar material STS304L SAW welded joints and design curve of JSSC.

Table 5 Average ultimate tensile strength, welding depth and width ratio and absorbed energy

Group no.	Ultimate tensile strength (MPa)	Depth and width ratio	Absorbed energy (J)
1	444	1.927	128
2	462	1.93	133
3	476	1.931	140
4	483	1.933	142
5	489	1.943	154
6	492	1.95	166
7	494	1.958	188
8	501	1.959	206
9	508	1.959	207
10	424	1.799	82
11	442	1.891	87
12	456	1.906	94
13	463	1.914	98
14	468	1.917	102
15	470	1.929	106
16	474	1.931	118
17	480	1.932	122
18	488	1.938	130

Table 6 Sequence of each performance characteristic after data preprocessing

Group no.	Ultimate tensile strength (MPa)	Depth and width ratio	Absorbed energy (J)
Reference sequence	1	1	1
1	0.232558	0.7911	0.359375
2	0.44186	0.809642	0.398438
3	0.604651	0.815822	0.453125
4	0.686047	0.828183	0.46875
5	0.755814	0.889988	0.5625
6	0.790698	0.933251	0.65625
7	0.813953	0.982695	0.828125
8	0.895349	0.988875	0.96875
9	0.976744	0.988875	0.976563
10	0	0	0
11	0.209302	0.568603	0.039063
12	0.372093	0.66131	0.09375
13	0.453488	0.710754	0.125
14	0.511628	0.729295	0.15625
15	0.534884	0.803461	0.1875
16	0.581395	0.815822	0.28125
17	0.651163	0.822002	0.3125
18	0.744186	0.859085	0.375

Table 7 Evaluated Grey relational coefficients and grades for 18groups

Group no.	Grey relational coefficient after weighted			Grey relational grade	
	UTS	D/W	AE	γ_i	Rank
1	0.3945	0.70532	0.43836	0.512723	13
2	0.47253	0.72426	0.4539	0.55023	11
3	0.55844	0.7308	0.47761	0.588952	8
4	0.61429	0.74425	0.48485	0.614461	7
5	0.67188	0.81966	0.53333	0.674955	5
6	0.70492	0.88222	0.59259	0.726578	4
7	0.72881	0.96655	0.74419	0.813182	3
8	0.82692	0.97823	0.94118	0.915445	2
9	0.95556	0.97823	0.95522	0.963005	1
10	0.33333	0.33333	0.33333	0.333333	18
11	0.38739	0.53683	0.34225	0.422154	17
12	0.4433	0.59617	0.35556	0.465008	16
13	0.47778	0.63352	0.36364	0.491643	15
14	0.50588	0.64876	0.37209	0.508911	14
15	0.51807	0.71783	0.38095	0.538953	12
16	0.5443	0.7308	0.41026	0.561788	10
17	0.58904	0.73747	0.42105	0.58252	9
18	0.66154	0.78014	0.44444	0.628706	6

Table 8 Response for the grey relational grade (*Optimal level)

Welding parameters	Level1	Level2	Level3	Max-Min
A	0.706615*	0.503668		0.202946
B	0.478733	0.592584	0.744108*	0.265374
C	0.554522	0.609036	0.651867*	0.097345
D	0.605636	0.603954	0.605835*	0.001881

Table 9. Results of welding performance using the initial and optimal welding process parameters

	Initial process parameters	Optimal process parameters
Level	A1B3C3D1	A1B3C3D3
UTS	502	508
D/W	1.948	1.959
AE	202	207

Table 10 Hybrid welding condition for dissimilar materials AH32-ST304L

Item	Welding condition	
CO ₂ Laser power(kW)	12	
GMAW	Wire type	AWS A5.9 ER309L
	Voltage(V)	27
	Current(A)	300
	CTWD(mm)	20
	Wire feeding speed (mm/min)	9.8
Welding speed(mm/min)	1,300	
Interspacing(mm)	4	
Gap(mm)	0	
Shielding gas	He65%, Ar32%, CO ₂ 3%	

Fatigue fracture occurred at STS304L side of BM in dissimilar materials hybrid welded joints. It can be inferred that because the specific strength of STS 304L is smaller than that of AH32, where STS 304L has approximately less than half yield stress and tensile strength than that of AH32.

From the figure, the fatigue curve obtained lied well above the design curve for JSSC. Dissimilar materials hybrid welded joints exhibited nearly the same as fatigue strength and limit of similar material STS304L SAW welded joints, however, exhibited lower fatigue limit than BM of STS304L. It was noteworthy that the welded joints of dissimilar materials exhibited similar fatigue strength to the STS304L SAW welded joints and lied well above the design curve (level D) for JSSC.

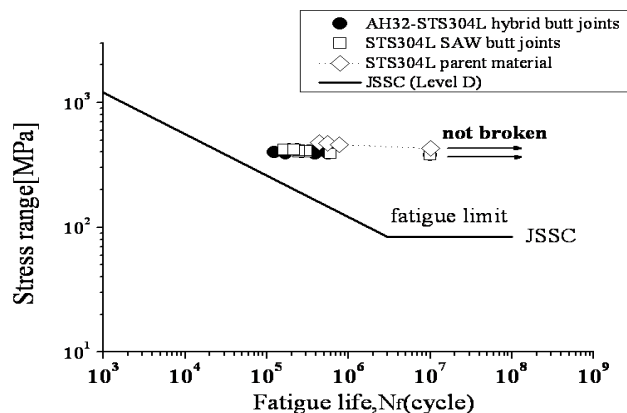


Fig. 4. S-N diagrams of the dissimilar materials hybrid welded joints

Conclusions

1 The optimum conditions for hybrid butt welded joints of 13mm AH32 and STS304L steel plate was current of 300 A, voltage of 27 V, welding speed of 1.3m/min, wire feeding speed of 9.8mm/min, shielding gases 65%He+32%Ar+3%CO₂, CTWD of 20mm, the spacing between the laser spot and the filler wire tip of 4 mm and laser power of 12kW.

2 It was found that the initial visual test of the welds can be classified as very stringent (Quality B') in quality levels for weld imperfections such as reinforcement, back-bead, undercut and uniformity of weld bead based on EN ISO 13919-1.

3 Tensile strength of hybrid welded joints was about 502MPa. In the tensile test of welded joints, the damaged part was in BM of STS304L side. Tensile strength of welded joints in dissimilar materials was comparable to that of STS304L base material.

4 Hardness values at distances of 3mm and 12mm over the bottom surface of welds were in the order of WM > HAZ > BM. The hardness at distance of 3mm over the bottom surface was higher than that at distance of 12mm over the bottom surface. The hardness of WM in AH32 was higher than that of STS304L due to its much more rapid heating and cooling rate. The hardness of hybrid welded joints exhibited within the acceptable range (the maximum value 340Hv~360Hv).

5 Dissimilar materials hybrid welded joints exhibited almost same fatigue strength for similar material STS304L SAW welded joints and lied well above the design curve(level D) for JSSC. This indicates that fatigue life was in excess of the design curve for arc welding. When the fatigue joints efficiency is defined as fatigue limit of welds by that of BM, fatigue joints efficiencies of welds was 88%.

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