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GREY-BASED TAGUCHI METHOD FOR OPTIMIZATION OF BEAD GEOMETRY IN LASER BEAD-ON-PLATE WELDING

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Abstract:
This study focused on the bead on plate welding of super austenitic stainless steel sheets using laser welding. Taguchi Technique is applied to plan and conduct the experiments. The output variables such as Bead Width (BW), Depth of Penetration (DP) and Aspect Ratio (AR) were measured from the bead on plate weld. These output variables were determined according to beam power, travel speed and focal position.

The bead on plate welding was performed on two different shielding gases like argon and helium. The shielding gas affects the weld bead characteristics such as shape, penetration-welding efficiency etc. It is appropriate to apply Taguchi's technique to a complex system like welding process. Therefore, this study is made to determine the near optimal welding process parameters (beam power, travel speed and focal position) using grey relational analysis by simultaneously considering multiple output parameters (bead width, depth of penetration and aspect ratio).

Taguchi experimental design for determining welding parameters was successful. The gray relational grade helped to quantify the integrated performance of bead on plate welding of laser beam welding process. Confirmation experiment has been conducted to validate the optimized parameters. The predicted and initial parameters have the better aspect ratio.

The optimal welding conditions were identified in order to increase the productivity and minimize the total operating cost. The process input parameters effect was determined under the optimal welding combinations.

Key Words: AISI 904 L Super austenitic stainless steel, laser welding, Bead Profile, Taguchi technique, Gray relational analysis

1. INTRODUCTION

Generally, the quality of a weld joint is directly influenced by the welding input parameters during the welding process. Therefore, welding can be considered as a multi-input and multi-output process. Traditionally, it has been necessary to determine the weld input parameters for every new welded product to obtain a welded joint with the required specifications. AISI 904 super austenitic stainless steel normally contains high amount of Mo, Cr, Ni, N and Mn. Since the steel retains its corrosion resistance at moderate and high temperature it is utilized extensively in the chemical, pulp paper and pollution control industries. Super austenitic stainless steels are the preferable materials for high corrosion resistance requirements. These steels are bridging the gap between relatively cheaper austenitic stainless steel and expensive nickel base super alloys for such applications. The microstructure of super austenitic stainless steels (SASS) consists of a fully austenitic structure in the solution-quenched condition. However, the high amount of alloying elements like Mo, N and Cr can enhance the precipitation of intermetallic phases. Laser welding has been used in many field of industry for its fast welding speed, low heat input, small heat affected zone and a large aspect ratio of weld depth to width. Laser welding with high power density, high degree of automation and high production rate is extremely and high production rate is extremely advantageous in automotive application [1]. The quality of the weld bead is dependent on a number of input process parameters, such as beam power, welding travel speed and focused position.

Manonmani et al. [2] have investigated the effect of the laser welding parameters on the bead geometry of 2.5 mm thick AISI304 stainless steel. In this study, the relationship between the process parameters (beam power, welding speed, and beam incidence angle) and the weld bead parameters (penetration, bead width and area of penetration) has been developed using RSM. To verify the developed models a conformity test run were carried out using intermediate values of the process parameters. It was confirmed that the model developed were accurate since the error percentages were between _4.317% and 3.914%. It was demonstrated that the depth of penetration and penetration area increase as the beam power and the beam angle increase. Also, as the welding speed increases, the width decreases, whereas the penetration depth and area increase to an optimum value and then decrease with further increases in welding speed. This is because the effect of key holing is predominant at lower speed and as the welding speed is increased the mode of heat transfer changes from key holing to conduction type of welding. It was reported that the variation in the bead width is slightly affected by the process parameters.

Benyounis et al. [3] have applied RSM to investigate the effect of laser welding parameters (laser power, welding speed and focal point position) based on four responses (heat input, penetration, bead width and width of HAZ) in CO2 laser butt-welding of medium carbon steel plates of 5 mm thick. They found that the heat input plays an imported rule in the weld-bead parameters; welding speed has a negative effect while laser power has a positive effect on all the responses.

Vitek et al. [4] have developed a model to predict the weld pool shape parameters (penetration, width, width at half-penetration and cross-section area) in pulsed Nd-YAG laser welds of Al-alloy 5754 using neural network. They have considered the following process parameters; travel speed, average power, pulse energy and pulse duration. They developed a routine to convert the shape parameters into a predicted weld profile that was based on the actual experimental weld profile data. The accuracy of the model was excellent. They concluded that this approach allows for instantaneous results and therefore, offers advantages in applications where real-time predictions are needed and computationally intensive predictions are too slow.

Lee et al. [5] have used the Taguchi method and regression analysis in order to optimize Nd-YAG laser welding parameters (nozzle type, rotating speed, title angle, focal position, pumping voltage, pulse frequency and pulse width) to seal an iodine-125 radioisotope seed into titanium capsule. The accurate control of the melted length of the tube end was the most important to obtain a sound sealed state. It was demonstrated that the laser pulse width and focal position were the laser welding parameters that had the greatest effects on the S/N ratios of the melted length. The optimal welding conditions were obtained at a pulse width of 0.86 ms and a focal position of 3.18–3.35 mm. Furthermore, confirmation experiments were conducted at the optimal welding conditions, it can be said that the titanium tube ends were sealed perfectly.

Pan et al. [6] have optimized laser butt-welding of a thin plate of magnesium alloy using the Taguchi method. They studied the effect of Nd-YAG laser welding parameters (shielding gas type, laser energy, conveying speed, laser focus, pulse frequency and pulse shape) on the ultimate tensile stress. Their result indicated that the pulse shape and energy of the laser contributed most to thin plate butt-welding. It was found that the optimal combination of welding parameters for laser welding were argon as a shielding gas, a 360 W laser energy, a work piece speed of 25 mm/s, a focus distance of 0 mm, a pulse frequency of 160 Hz and type III pulse shape. It was also found that the superior ultimate tension stress was 169 MPa at an overlap of the welding zone of approximately 75%.

In the present paper, an attempt has been made to carry out the experiments based an L8 orthogonal array. Though several studies made on weld quality by considering response variables separately, literature on simultaneous consideration of response variables is scarce. This study introduced to determine the near optimal welding process parameters using grey relational analysis by simultaneously considering multiple output parameters. Therefore, it is appropriate to apply this technique to a complex system like welding process. Through this technique, the welding parameters were evaluated and compared with the experimental results.

2. GREY – BASED TAGUCHI METHOD FOR PARAMETRIC OPTIMIZATION

Genichi Taguchi, a Japanese scientist, developed a technique based on orthogonal array (OA) of experiments. OA and S/N ratios are used to study the effects of control factors and noise factors, and to determine the best quality characteristics for particular applications. However, originally Taguchi method was designed to optimize single performance characteristics. This technique has been widely used in different fields of engineering to optimize the process parameters [7, 8]. The integration of DOE with parametric optimization of process can be achieved in the Taguchi's signal-to-noise (S/N) ratios, which are logarithmic functions of the desired output, serve as objective functions for optimization. It helps to learn the whole parameter space with a small number (minimum experimental runs) [9] of experiments. The optimal process parameters obtained from the Taguchi method are insensitive to the variation of environmental conditions and other noise factors [10]. Optimization of multiple performance characteristics is not straightforward and much more complicated than that of single performance characteristics. To solve the multiple performance characteristics problems, the Taguchi method is coupled with grey relational analysis. Deng first proposed grey relational analysis in 1982 [11] to fulfill the crucial mathematical criteria for dealing with poor, incomplete, and uncertain systems [12]. This grey-based Taguchi technique has been widely used in different fields of engineering to solve multi-response optimization problems. In order to apply the grey-based Taguchi method for multi-response optimization, the following seven steps are followed:

Step 1: Identification of quality characteristics. This involves complete understanding of the problem and identification of the major quality characteristics. In this research, the joint quality can be evaluated by studying the features of weld bead geometry such as Bead width (BW), Depth of penetration (DP) and Aspect ratio (AR) namely BW, DP and AR.

Step 2: Identification of control factors and noise factors. Control factors are those that can be varied by the operator. Noise factors are those influences that cannot be altered by the operator.

Step 3: Selection of factor levels. This step concerns to selection of the range of input parameters so that it would be safe for setting parameters at levels where experiments would not end in a failure. In this work, sufficient numbers of trial experiments have been carried out to find the parameter ranges in which effective welding takes place without failure (such as power failure due to short circuit and discontinuous arching).

Step 4: Design of an appropriate orthogonal array matrix. A suitable OA design is crucial for the success of an analysis. This depends on the total degrees of freedom (DOF) required to study the main and interaction effects, the goal of the experiments, resource and budget availability, and the time constraints. In this case, nine degrees of freedom are required for studying the four factors with three levels. Only the main effects are considered in this study. So an L8 orthogonal array has been selected to conduct the study.

Step 5: Conducting the experiments according to the design matrix. This phase concerns conduction of the experiments and output data collection. The detailed experimental procedure is given in section 3.

Step 6: Statistical analysis and determination of optimal levels for control factors. In order to evaluate the optimal process parameters settings, the Taguchi method uses a statistical measure of performance.

This is true for the optimization of a single quality characteristic. To consider several quality characteristics together in the selection of optimal process parameters, the Taguchi method need to be modified to include several loss functions corresponding to different quality characteristics. The grey based Taguchi method was used to integrate the loss function and obtain the optimum parameter settings.

Step 7: Perform a verification run of the experiment. In this step, by using the results of the optimization study, which was carried out in the previous step, a validation experiment is performed. Finally, the predicted overall grey relational grade is compared with the experimental run.

2.1 Grey relational analysis

In the grey relational analysis, experimental data, i.e., measured quality characteristics, are first normalized in the range of 0 to 1. This process is called grey relational generation. Based on this data, grey relational coefficients are calculated to represent the correlation between the ideal (best) and the actual normalized experimental data. Overall, grey relational grade is then determined by averaging the grey relational coefficients corresponding to selected responses. The overall quality characteristics of the multi-response process depend on the calculated grey relational grade.

2.2 Grey relational generation

There are three different types of data normalization according to the requirement of Lower the Better (LB), Higher the Better (HB), or Not Better (NB) criteria. The desired quality characteristics for depth of penetration are the HB criterion. Therefore, the normalization of original sequence of these three responses is done using “equation 1”.

$$yi\,^*(k) = \frac{yi(k) - minyi(k)}{maxyi(k) - minyi(k)} \tag{1}$$

Where yi*(k) is the normalized data, i.e. after grey relational generation, yi(k) is the kth response of the ith experiment, min yi(k) is the smallest value of yi(k) for the kth response, and max yi(k) is the largest value of yi(k) for the kth response.

Bead width follows the LB criterion. Accordingly, the normalization of these responses is done using “equation 2”.

$$yi\,^*(k) = \frac{maxyi(k) - minyi(k)}{maxyi(k) - minyi(k)} \tag{2}$$

2.3 Grey relational coefficient

The grey relational coefficient is calculated as

$$\varepsilon_i\,(k) = \frac{\Delta\min + \varpi\,\Delta max}{\Delta 0i(k) + \varpi\,\Delta max} \tag{3}$$

where is the grey relational coefficient of the i^{th} experiment for the k^{th} response, $\Delta_{oi}\,(k) = ||y^*_o(k) - y^*_i(k)||$, i.e. , absolute of the difference between $y^*_o(k)$ and $y^*_i(k)$, $y^*_o(k)$ is the ideal or reference sequence, $\Delta_{max} = \max_i \max_k ||y^*_o(k) - y^*_i(k)||$ is the largest value of Δ_{oi} , and $\Delta_{min} = \max_i \max_k ||y^*_o(k) - y^*_i(k)||$ is the smallest value of Δ_{oi} , and ω(0≤ ω ≤ 1 is the distinguish coefficient [16].

2.4 Grey relational grade

The grey relational grade (Γi) is calculated by averaging the grey relational coefficients corresponding to each experiment.

$$\Gamma i = \frac{1}{}\sum_{=1}^{Q} i(k) \tag{4}$$

Where, Q is the total number of responses. A high grey relational grade corresponds to intense relational degree between the given sequence and the reference sequence. The reference sequence, $y^*_o(k)$, represents the best process sequence; therefore, higher grey relational grade means that the corresponding parameter combination is closer to the optimal setting.

3. EXPERIMENTAL PROCEDURE

904 L Super austenitic stainless steel sheets of 100mm length, 50mm width and 5mm thick were used in the present study. The nominal chemical composition of the base material is given in the Table. I.

Table I: Base material chemical composition (weight in %).

Material	Si	Mn	P	S	Cr	Ni	Mo	C	Cu
Base Material	0.374	1.522	0.018	0.004	19.893	25.557	4.124	0.018	1.65

The welding was carried our using on Diffusion-cooled slab 3.5 kw Co_2 laser welding machine. Argon and helium gas at a flow rate of 30 lit/min was used as a shielding gas. In this study, L8 orthogonal array that has an 8 degree of freedom was used. Eight experiments are required to study the entire welding parameters space when the L8 orthogonal array is used. The experimental layout for the Laser welding parameters using the L8 orthogonal array is show in Table II.

Table II: L8 orthogonal array.

Experiment No	Beam Power	Travel Speed	Focal Position
1	1	1	1
2	1	2	2
3	2	1	1
4	2	2	2
5	2	1	2
6	2	2	1
7	1	1	2
8	1	2	1

The working range of the laser welding parameters like Beam power, travel speed and focal position were kept fixed to (3 & 3-5 kw), (1 & 2m/min), and (0 &-2 mm) respectively, and other parameters like stand off distance (4.5 mm), nozzle position (45^0), and beam diameter (25 mm) were fixed as a constant. The welding parameters were given in the Table III.

Table III: Range of the welding parameters.

Parameters	Level 1	Level 2
Beam Power (kW)	3	3.5
Travel Speed (m/min)	1	2
Focal Position (mm)	0	-2

Weld profiles were obtained by sectioning and polishing with suitable abrasive and diamond paste. Weld samples were etched with 10% oxalic acid an electrolytic to reveal increase the contrast of the fusion zone with the base metal. The bead profiles were measured on the etched sample using optical microscopy. The experimental results for the weld pool geometry using the L8 orthogonal array are shown in Table IV.

Table IV: Experimental Results for Argon & helium shielding gas.

Ex. No.	Shielding gas	Beam power	Travel speed	Focal position	Bead width (mm)	Depth of penetration (mm)	Aspect ratio
1	Ar	3	1	0	2.908	5.534	1.903026
	He	3	1	0	2.787	5.445	1.953713
2	Ar	3	2	-2	2.311	5.555	2.403721
	He	3	2	-2	2.034	5.415	2.662241
3	Ar	3.5	1	0	2.162	4.86	2.247918
	He	3.5	1	0	1.964	5.386	2.742362
4	Ar	3.5	2	-2	3.828	5.02	1.31138
	He	3.5	2	-2	3.362	5.494	1.634146
5	Ar	3.5	1	-2	2.926	5.347	1.827409
	He	3.5	1	-2	2.122	5.418	2.553251
6	Ar	3.5	2	0	4.276	5.435	1.271047
	He	3.5	2	0	3.324	5.376	1.61732
7	Ar	3	1	-2	2.638	4.991	1.891963
	He	3	1	-2	2.163	5.407	2.49976
8	Ar	3	2	0	3.154	5.316	1.685478
	He	3	2	0	2.986	5.528	1.851306

4. RESULTS AND DISCUSSIONS

4.1 Implementation of Grey relational analysis

Table IV lists the mean Bead Width (BW), Depth of penetration (DOP) and Aspect ratio (AR) along the welding path for eight measured samples for both the shielding gases (argon and helium) were presented. Table VI shows the grey relational grade for argon shielding gas and Table VII shows the grey relational grade for helium shielding gases were evaluated for each sample is presented in the same Tables. The normalized values for BW, DOP and AR were calculated by the equation (1) and (2). The grey relational co efficient for BW, DOP and

AR were calculated by the equation (3) and the grey relational grade was computed by the equation (4) as presented in the same table. As shown, the third experiment listed in Table IV has the highest grade of 0.788995591, experiment number 4 and 7 have the second and third highest grade of 0.66880244 and 0.630913352 for argon shielding gas and the helium shielding gases, the sixth experiment has the highest grade of 0.779828396, experiment number 3 and 2 have the second and third highest grade of 0.739018088 and 0.639930077 respectively. The optimum level for a factor is the level that gives the desired quality characteristics in the experimental region. The main effects of factors are computed and presented in Table V. The main effects are calculated by referring the grey relational grade values and their corresponding orthogonal array table. From this table, it is understood that the optimal parameter (for argon and helium both the shielding gas) setting are (1) Beam Power 3.5 kw; (2) Travel Speed 1 m/min; (3) Focal Position 0 mm corresponding to the maximum grey relational grade.

Table V: Main effects.

Factors	Shielding gas	LEVEL-1	LEVEL-2
Beam Power(KW)	Argon	0.530057198	**0.632060914**
	Helium	0.571056779	**0.673975107**
Travel Speed (m/min)	Argon	**0.59667319**	0.565444893
	Helium	**0.628276454**	0.616755432
Focal Position (mm)	Argon	**0.58348687**	0.578631242
	Helium	**0.634288095**	0.610743791

The relative contributions of the factors are determined from the analysis of variance (ANOVA). The purpose of the ANOVA is to investigate which welding process parameters significantly affect the quality characteristics. The percentage contribution by each of the process parameters in the total sum of the squared deviations can be used to evaluate the importance of the process parameters change on the quality characteristics. In addition, the F- test was used to determine which welding process parameters have a significant effect on the quality characteristics. Generally, the change of the welding process parameter has a significant effect on the quality characteristics when the F value is large (Table VI and Table VII).

Table VI: Evaluated Grey Relational grades for argon shielding gas.

Exp. No.	Normalized values			Gray Relational Analysis			Gray Relational Coefficient			Grade
	BW	DOP	AR	BW	DOP	AR	BW	DOP	AR	
1	0.64	0.03	0.44	0.35	0.96	0.55	0.58	0.34	0.47	0.46
2	0.92	0	0	0.07	1	1	0.87	0.33	0.33	0.51
3	1	1	0.13	0	0	0.86	1	1	0.36	0.78
4	0.21	0.76	0.96	0.78	0.23	0.03	0.38	0.68	0.93	0.66
5	0.63	0.29	0.50	0.36	0.70	0.49	0.58	0.41	0.50	0.50
6	0	0.17	1	1	0.82	0	0.33	0.37	1	0.57
7	0.77	0.81	0.45	0.22	0.18	0.54	0.68	0.72	0.47	0.63
8	0.53	0.34	0.63	0.46	0.65	0.36	0.51	0.43	0.57	0.50

Table VII: Evaluated Grey relational grade for helium shielding gas.

Exp. No.	Normalized values			Gray Relational Analysis			Gray Relational Coefficient			Grade
	BW	DOP	AR	BW	DOP	AR	BW	DOP	AR	
1	0.41	0.54	0.70	0.58	0.45	0.29	0.45	0.52	0.62	0.53
2	0.94	0.74	0.07	0.05	0.25	0.92	0.90	0.66	0.34	0.63
3	1	0.93	0	0	0.06	1	1	0.88	0.33	0.73
4	0	0.22	0.98	1	0.77	0.01	0.33	0.39	0.97	0.56
5	0.88	0.72	0.16	0.11	0.27	0.83	0.81	0.64	0.37	0.61
6	0.02	1	1	0.97	0	0	0.33	1	1	0.77
7	0.85	0.79	0.21	0.14	0.20	0.78	0.77	0.71	0.38	0.62
8	0.26	0	0.79	0.73	1	0.20	0.40	0.33	0.70	0.48

Results of ANOVA for both the shielding gases are presented in Table VIII and Table IX. From Table VIII and Table IX, the contribution of focal position is least significant when compared to other factors. The beam power and travel speed are the major contributors in affecting the response values and these factors are the significant factors.

Table VIII: ANOVA Results for Argon shielding gas.

Parameters	Sum of Square	Degree Of Freedom	Mean Square Deviation	F-Statistics	% of contribution
Beam Power	0.020809	1	0.020809	4.14247	17.212
Travel Speed	0.021950	1	0.021950	4.36959	18.156
Focal Position	0.018047	1	0.018047	3.59258	14.927
ERROR	0.06009	4	0.005023	--	49.70

Table IX: ANOVA Results for Helium shielding gas.

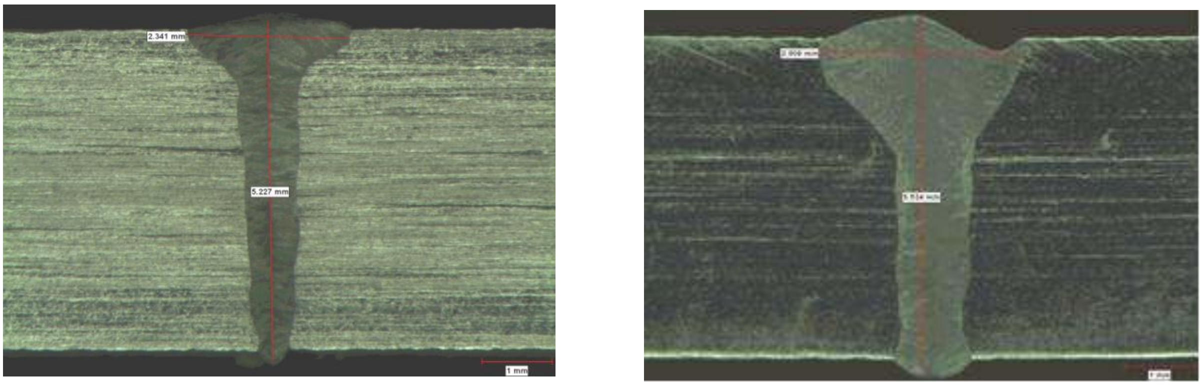
Parameters	Sum of Square	Degree Of Freedom	Mean Square Deviation	F-Statistics	% of contribution
Beam Power	0.021184	1	0.021184	3.741497	21.35
Travel Speed	0.020265	1	0.020265	3.579206	20.42
Focal Position	0.011108	1	0.011108	1.961968	11.19
ERROR	0.046648	4	0.005662	--	47.02

4.2 Confirmation tests

Based on the preliminary trails, the initial parameters were chosen, the bead on plate weld was made, and the bead profiles were measured. A confirmation experiment has carried out to validate the results and it has been compared with the initial condition. Table X reflects the satisfactory results of confirmatory experiment. From the Table 10, the predicted bead profiles have the better depth of penetration and lesser bead width. The comparative bead profiles are presented in Figure 1. It can be clearly understood that, the better bead profile characteristics are observed from the predicted parameters.

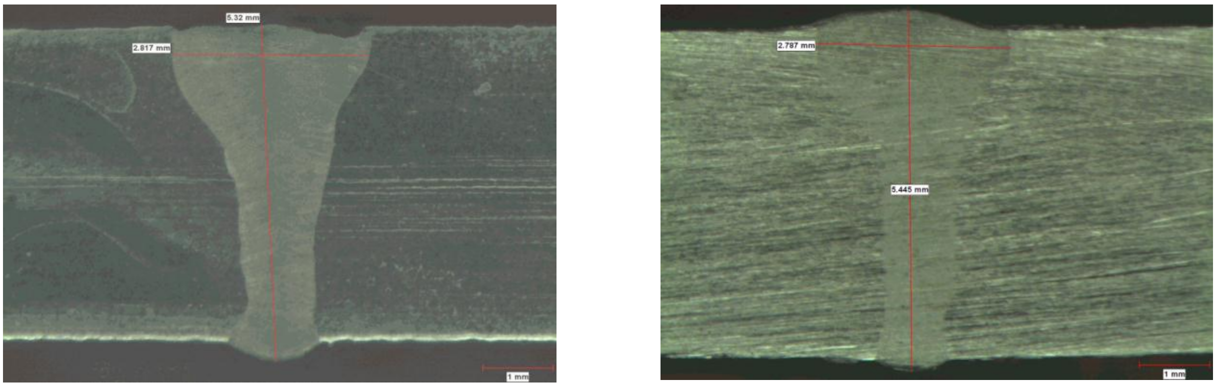
Table X: Results of confirmatory experiment.

	Shielding gas	Beam power	Travel speed	Focal position	Bead width (mm)	Depth of penetration (mm)	Aspect ratio
Initial parameter	Ar	3.5	1	0	2.908	5.534	1.9030
	He	3.5	1	0	2.787	5.445	1.9537
Predicted parameter	Ar	3.5	1	0	2.341	5.227	2.2328
	He	3.5	1	0	2.817	5.32	1.8885



(a) Initial parameter-Argon gas

(b) Predicted parameter-argon gas



(c) Initial parameter-helium gas

(d) Predicted parameter-helium gas

Figure 1(a-d): Comparative bead profiles.

5. CONCLUSIONS

The important results in this study

1. 904 L super austenitic stainless steel sheet is successfully bead on plate welded by laser beam welding process and the bead profiles were measured.
2. The calculation of the gray relational grade helped to quantify the integrated performance of bead on plate welding of laser beam welding process.

3. The complex interactions in laser beam welding process involved the beam current, travel speed and focal position.
4. The optimization of laser beam welding process of 904 L super austenitic stainless steel, by calculating the gray relational grade and using the recommendation of Taguchi experimental design for determining welding parameters was successful.
5. For the optimized parameters, the bead on plate welds are processed and compared with the initial conditions.
6. The predicted and initial parameters have the better aspect ratio.

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