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Investigation of Optimal Parameter Settings in Super Duplex Welding

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***Abstract*—**Super steel materials play a vital role in the construction and fabrication of structural, piping and pipeline components. In assuring the integrity of onshore and offshore operating systems, they enable life cycle costs to be minimized. In this context, Duplex stainless steel (DSS) material related welding on constructions and fabrications plays a significant role in maintaining and assuring integrity at an optimal expenditure over the life cycle of production and process systems as well as associated structures. In DSS welding, factors such as gap geometry, shielding gas supply rate, welding current, and type of the welding process are vital to the final joint performance. Hence, an experimental investigation has been performed using an engineering robust design approach (ERDA) to investigate the optimal settings that generate optimal super DSS (i.e. UNS S32750) joint performance. This manuscript illustrates the mathematical approach and experimental design, optimal parameter settings and results of the verification experiment.

***Keywords*—**Duplex stainless steel welding, engineering robust design, mathematical framework, optimal parameter settings.

I. INTRODUCTION

THE DSS welding on onshore and offshore constructions and operating systems plays a significant role in assuring structural integrity [1]. It is vital to establish welding procedure specifications (WPSs) before starting the formal fabrication process [2]. Inherently, welding provides a reliable and efficient metal-joining process to almost all kinds of steel fabrications and constructions [3]. However [1] and [4] indicate that it is a multi-input (e.g. human skills, level of automation, mechanics, energy, gas/flux, welding intensity, welding speed, material composition, arc length, etc.) and multi-output (e.g. weld seam geometry, weld seam quality, residual stresses and resulting geometrical changes, metallurgical changes, etc.) process, as the acceptable quality level of a welded joint is directly dependent on input parameters during the welding process.

It is a challenge for a fabricator or constructor to control the process input parameters (e.g. joint geometry, shielding gas flow rate, etc.) to obtain an acceptable welded joint, which is fit for purpose within the specified parameters (e.g. ultimate joint strength (UJS), bead geometry, weld quality with minimal detrimental stresses and distortion, etc.) [5]. Based on the required specifications (e.g. according to welding codes) demanded by the client, conventionally it has been necessary to recognize the weld input parameters for each newly introduced welded fabrication [5]. In order to achieve the aforementioned, a time-consuming trial and error development effort is required (i.e. due to lack of mathematical formulations based on the weld input parameters selected by the skill of welding experts (e.g. welding engineers, technicians, etc.) [6].

This manuscript illustrates the use of an ERDA-based mathematical framework with the support of experimentation and analysis for establishing optimal parameter settings in super DSS welding [7]. Finally, it verifies the results for duplex stainless steel UNS S32750 and concludes on the possible use of the suggested approach for developing WPSs in general.

II. BACKGROUND

In most fabrication or construction organizations, engineers and managers are unaware of the benefits of using the ERDA approach for improving the quality of fabricated or constructed items. Instead, they tend to use more costly parts, components, and/or machinery for improving the quality, without first obtaining most of the benefits of the ‘parameter design’ approach along with the existing equipment and their settings [8]. Consequently, fabrication or construction organizations lose the opportunity to improve quality without increasing cost. Hence, this leads to the misconception that higher quality always results in increased unit fabrication cost.

Although the ‘parameter design’ should not lead to a significant increase in the fabrication costs, a research and development (R&D) budget is needed to explore the nonlinear effects of various control factors. However, the use of RDA along with orthogonal arrays and signal-to-noise (S/N) ratios more significantly reduces the R&D budget than studying one control factor at a time, the use of ad hoc methods for finding the best values of many control factors simultaneously or the implementation of conventional experiment designs [9]. In this context, ‘signal factors’ are defined as the parameters set by the user or operator of the item (i.e. to be fabricated or constructed) to meet the target quality level. The ‘noise factors’ are defined as the parameters that cannot be controlled by the designer.

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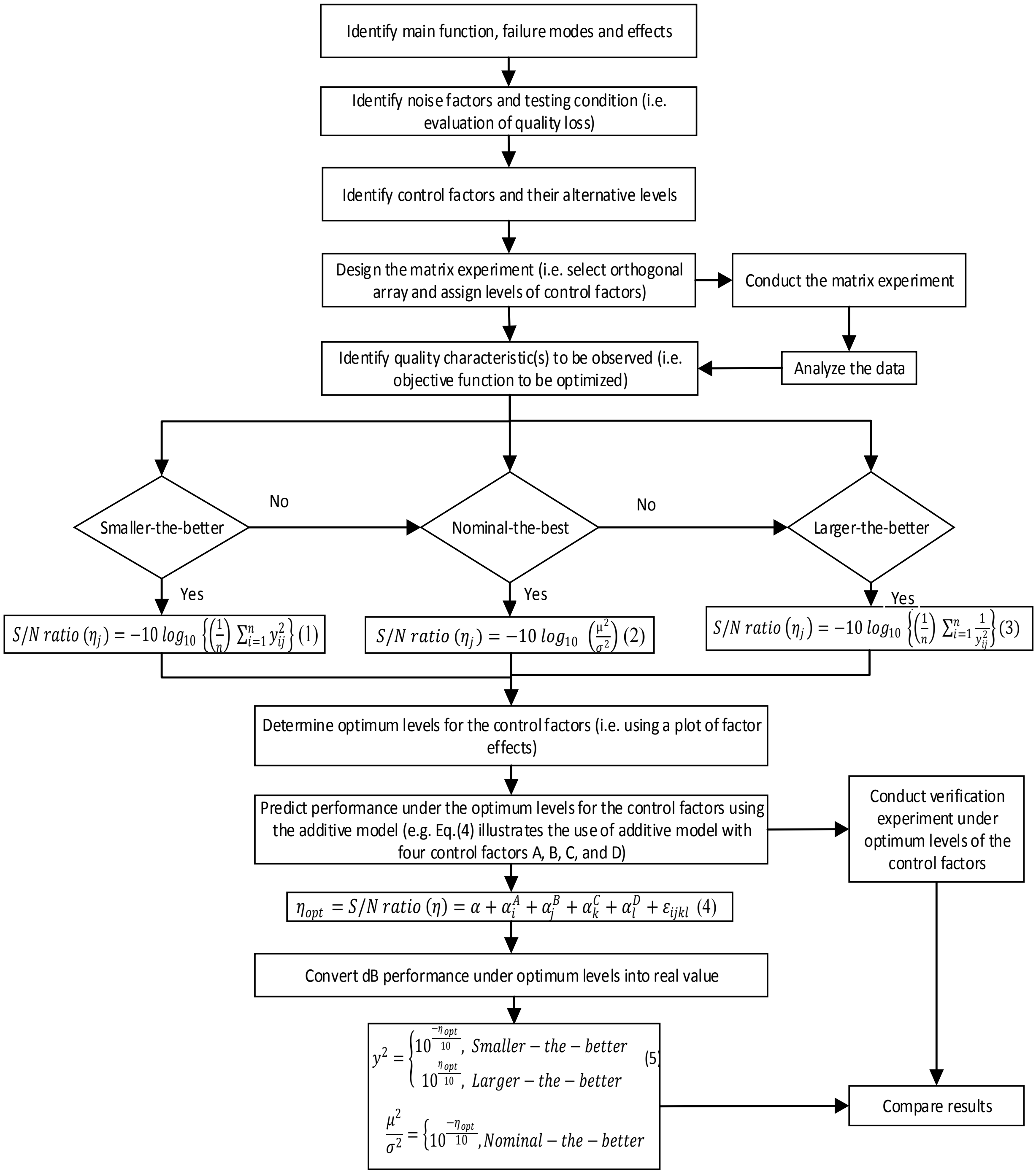

Fig. 1 Mathematical framework for parameter designing under the noise

The factors whose settings are difficult or expensive to control are also referred to as noise factors. Instead of actual values in specific situations, only the statistical characteristics (such as the mean and variance) of noise factors are known or specified. The 'control factors' are defined as the parameters that can be specified freely by the parameter designer. However, the parameter designers are responsible for determining the optimal values in such a way that settings (or levels) are selected to minimize the sensitivity of the fabricated or constructed item's response to all noise factors [10]. The control factors which affect the cost of the fabricated or constructed items are referred to as 'tolerance factors'.

III. Methodology

An experimentation and mathematical approach (i.e. a framework) has been suggested using ERDA for establishing limits to the parameter design (see Fig. 1), which involves the selection of optimum levels of the control factors to maximize the robustness (i.e. robust joint performance). The selection of the correct objective function to maximize or minimize an engineering design problem is vital. In this context, the problems encountered in designing are broadly divided into two categories: 1. Static problems, i.e. when a fixed target is involved (e.g. minimizing surface defect count, meeting target thickness, etc.); 2. Dynamic problems, i.e. when a fixed target is not involved (e.g. the design of an electrical amplifier involves tracking of the input signal by the output signal, which makes it a dynamic problem) [11].

A. Experimental and Analytical Approach

The experimental and analysis approach is illustrated in Fig. 1. It provides a framework for parameter design under the existing noise. The quality characteristics: larger-the-better (e.g. metal removal rate), nominal-the-best (e.g. meeting target thickness in foam) and smaller-the-better (e.g. surface roughness) have been taken into consideration in developing the framework [8], [12], [13]. In this context, the quality characteristic is referred to as the response of a fabricated or constructed item that is observed for the purpose of evaluating the quality loss or optimizing the performance of a fabricated or constructed item (or design). The notation for each variable is as follows:

- n = number of replications
- y_{ij} = performance indicator value (i = 1,2…n and j = 1,2…m), where m = number of experiments

$$\mu = \frac{1}{n}\sum_{i=1}^{n} y_i$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n} (y_i - \mu)^2$$

- α = overall mean S/N ratio over all the possible combinations
- i,j,k,l = particular levels of each of the factors which were selected (so in this model i, j, k and l must all take on one of the values 1, 2 or 3)
- α_i^A = deviation from α caused by setting factor A at level i (similarly, other terms can be defined for B, C and D)
- ε_{ijkl} = error term

IV. Experimental Setup, Factors and Factor Levels

A. Background

Duplex stainless steels (DSS) with a dual-phase micro-structure comprise nearly equal amounts of ferrite and austenite, which provide super material property combinations [14], [15]. Nitrogen is commonly added into DSSs to enhance mechanical strengthening, the corrosion resistance of the material and for the equilibrium balance of ferrite and austenite [16]. One of the possible precipitates in the DSSs is chromium nitride. Hence, it has become an important issue with the increasing use of high chromium and high nitrogen contents in modern DSSs [17], [18]. Variations in base and filler metal nitrogen contents and nitrogen pickup from the atmosphere during welding can result in weld metal nitrogen contents ranging from below 0.04 to above 0.3wt-% [17]. In general, nitrogen (i.e. a strong austenite former) is an important alloying element; in the super/hyper duplex steels, about 1 to 2% nitrogen is added to the shield gas to compensate for any loss of nitrogen from the weld pool. However, nitrogen addition has a tendency to increase the speed of erosion of the tungsten electrode. Hence, purging the back face of a joint is essential when depositing a gas tungsten arc welding (GTAW) (i.e. also known as tungsten inert gas (TIG)) root pass. Essentially, for the first couple of fill passes, pure argon is used with added small amounts of nitrogen. However, pure nitrogen has rarely been used [18]. Fig. 2 illustrates the parameters, which affect the final weld metal nitrogen content in general [19].

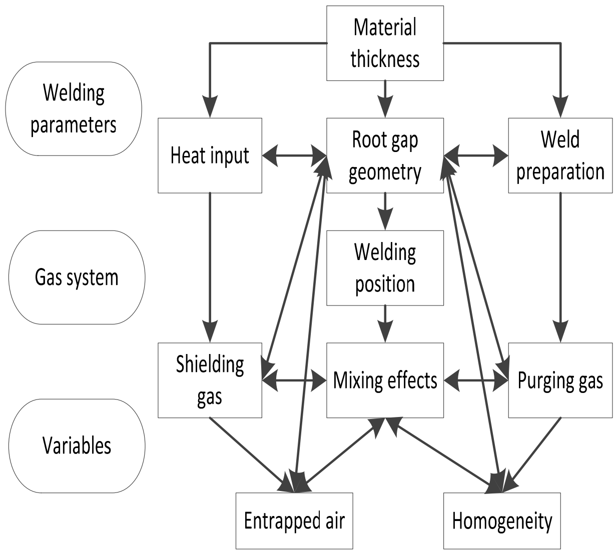

Fig. 2 The parameters which affect the final weld metal nitrogen content [19]

Welding processes also have an influence on the final joint performance. For instance, although GTAW welding provides significantly clean weld metal with good strength and toughness, together with the possibility of mechanization, it is not recommended on duplex steels as the corrosion resistance is considerably impaired. However, if GTAW is preformed, then filler metals have to be selected to match the composition of the parent metal (i.e. with an additional 2 to 4% nickel) to ensure that sufficient austenite is formed [18]. On the other hand, it is possible to carry out shielded metal arc welding (SMAW) with matching composition electrodes which have been over-alloyed with nickel and either rutile or basic flux coatings. SMAW basic electrodes give better notch toughness values, and electrodes of up to 5 mm diameter are available with the smaller diameters providing the best positional control [18]. The DSS welding is generally carried out with gas metal arc welding (GMAW) (also called metal inert gas (MIG) welding or metal active gas (MAG) welding) using “wires of 0.8 to 1.2 mm diameter, rarely exceeding 1.6 mm and of a similar composition to the GTAW wires” [18]. For GMAW of DSS, shielding gases are used; these are based on high purity argon with additions of carbon dioxide or oxygen, helium and perhaps nitrogen [18]. Shielding gases are vital, as, in the presence of carbon dioxide or oxygen, the weld metal notch toughness values are less than that which can be achieved using GTAW. In this context, microprocessor-controlled pulsed welding provides the best combination of mechanical properties [18].

Welding geometry such as root gaps, root faces and joint angles have been selected based on the requirements such as maximization of production, minimization of parent metal dilution in the root, and control of the heat input [20]. Hence, the control of the root gap and geometry has been considered as an important factor [20].

B. Material Data

The chemical specifications of the DSS (i.e. UNS S32750) that has been used for the welding experiments are illustrated in Table I.

TABLE I
CHEMICAL SPECIFICATION OF UNS S32750

Elements	C	Cr	Cu	Fe	Mo	Mn	N	Ni	P	S	Si	W
Minimum		24.00		Remainder	3.00		0.24	6.00			0.20	0.50
Maximum	0.0300	26.000	0.500		5.000	1.200	0.320	8.000	0.035	0.020	0.800	1.000

The basic mechanical properties of UNS S32750 are illustrated in Table II.

TABLE II
BASIC MECHANICAL PROPERTIES OF UNS S32750

Mechanical property	Value
0.2% proof stress (N/mm^2) (ksi) minimum	550 (79.8)
Ultimate tensile strength (N/mm^2) (ksi) minimum	800(116)
Elongation (%) minimum	25
Hardness (HBN)	270 max
Reduction of cross section area (%)	45
Charpy V-notch impact at ambient temperature (J) (ft. lb)	80min (59min)
Charpy V-notch impact at -46^{0}C ambient temperature (J) (ft. lb)	45av, 35min (33av, 25.8min)

The chemical compositions of the filler material used for GTAW and GMAW are given in Table III.

TABLE III
CHEMICAL COMPOSITIONS OF GTAW AND GMAW FILLER MATERIALS

Welding process	Heat no.	Chemical composition (weight %) of the filler material				
GTAW	530958	C (0.012)	Si (0.41)	Mn (0.39)	P (0.016)	S (0.0008)
		Cr (25.09)	Ni (9.27)	Mo (3.90)	W (< 0.01)	Co (0.12)
		V (0.057)	Ti (< 0.003)	Cu (0.085)	Nb (0.01)	N (0.24)
GMAW	522832	C (0.010)	Si (0.38)	Mn (0.44)	P (0.018)	S (0.0007)
		Cr (25.11)	Ni (9.44)	Mo (3.90)	W (< 0.01)	Co (0.040)
		V (0.058)	Ti (< 0.003)	Cu (0.11)	Nb (0.01)	N (0.25)

C. Experimental Setup

The control factors, joint geometry (A), shielding gas feed rate (B), welding current (C), and welding process (D), have been selected as the parameters to be designed to achieve the optimal ultimate joint strength (UJS) (i.e. quality characteristic to be observed) [22]-[24]. The joint strength has been measured using an INSTRON tensile testing machine. The objective function, 'larger-the-better' has been selected, as the maximum possible strength values have been selected to assess the welded joint performance. The factor levels have been established using experts' knowledge and relevant literature (see Table IV).

TABLE IV
FACTOR LEVELS

Factor	Factor level 1	2	3
A	Standard opening with a nose (3.2 mm)	Standard opening without a nose (3.2 mm)	Standard opening with a nose (4.0 mm)
B	Pure argon (20 *l/min*)	Pure argon (17 *l/min*)	Argon (15 *l/min*)
C	182 A	168 A	160 A
D	Backing + GMAW	GMAW	GTAW

The ERDA is structured to recognize the optimum combinations of the input parameters, based on the statistical results generated from test matrix experiments [21], [8]. The standard orthogonal array *L9* (see Table V) has been used to conduct the case study matrix experiment.

TABLE V
THE STANDARD ORTHOGONAL ARRAY L9

Experiment number	*A*	*B*	*C*	*D*
1	*1*	*1*	*1*	*1*
2	*1*	*2*	*2*	*2*
3	*1*	*3*	*3*	*3*
4	*2*	*1*	*2*	*3*
5	*2*	*2*	*3*	*1*
6	*2*	*3*	*1*	*2*
7	*3*	*1*	*3*	*2*
8	*3*	*2*	*1*	*3*
9	*3*	*3*	*2*	*1*

D. Results of the Matrix Experiment

Table VI illustrates levels of input factors and S/N ratios {using (3)} of output (i.e. UJS) for each of nine experiments. The factor levels were recognized based on experts' knowledge and published research data.

TABLE VI
LEVELS OF INPUT FACTORS AND (S/N) RATIOS OF OUTPUT (I.E. UJS)

Experiment number	Input parameter levels *A*	*B*	*C*	*D*	UJS (y_i) (N/mm^2)	(S/N) ratio (dB)
1	*1*	*1*	*1*	*1*	788.776	57.93
2	*1*	*2*	*2*	*2*	782.139	57.86
3	*1*	*3*	*3*	*3*	758.995	57.59
4	*2*	*1*	*2*	*3*	756.950	57.57
5	*2*	*2*	*3*	*1*	722.935	57.17
6	*2*	*3*	*1*	*2*	762.121	57.64
7	*3*	*1*	*3*	*2*	728.604	57.24
8	*3*	*2*	*1*	*3*	773.321	57.77
9	*3*	*3*	*2*	*1*	771.343	57.74

The average η for each level of the four factors is calculated and listed in Table VII.

TABLE VII
AVERAGE H BY FACTOR LEVELS

Factor	Factor level/ (dB)		
	1	2	3
A	57.80*	57.46	57.58
B	57.58	57.60	57.65*
C	57.78*	57.72	57.33
D	57.62*	57.58	57.54

Overall mean = 57.61. Starting level is identified by an underscore, and the optimum level is identified by *.

The plot of factor effects for the joint tensile strength is presented in Fig. 3.

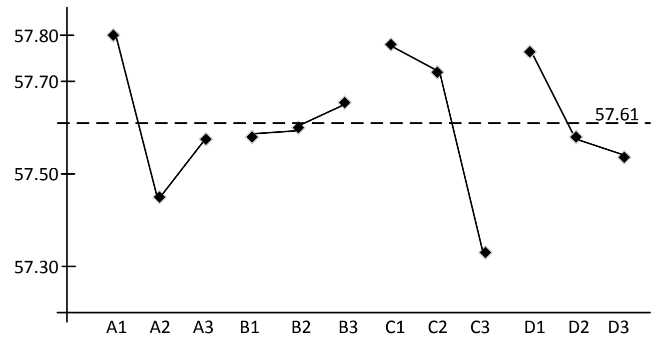

Fig. 3 Plots of factor effects (factor levels at the best tensile strength are L_{A1}-L_{B3}-L_{C1}-L_{D1})

Best settings and the corresponding theoretically calculated optimum value {using (4) and (5)} of the output quality characteristic (i.e. UJS) is summarized in Table VIII.

TABLE VIII
THEORETICALLY CALCULATED VALUE OF OUTPUT QUALITY CHARACTERISTIC

Output quality characteristic	Best parameter levels combination	η_{opt} (dB) {using (4)}	Theoretically calculated UJS/ (N/mm^2) (Using (5))
UJS	L_{A1}-L_{B3}-L_{C1}-L_{D1}	57.97	791.60

Using the optimum values of the output parameter levels estimated (i.e. using the designed parameters) by the matrix experiment, a verification experiment was performed. This is to verify that the designed parameter values generate improved results {i.e. to verify whether the theoretically calculated output parameter value (see 4th column of Table VIII) can be obtained when the DSS welding is repeated with optimum values of the control factor levels}.

E. Results of the Verification Experiment

A verification experiment was performed to verify the theoretically calculated output values. The result is summarized in Table IX.

V. DISCUSSION

The summary of the joint performance for DSS welding, i.e. the theoretically calculated optimum value {i.e. using (4)} and the experimentally measured value of UJS (i.e. from the verification experiment), are summarized in Table X.

TABLE IX
RESULTS OF VERIFICATION EXPERIMENT

Output quality characteristic	Best parameter levels combination	Experimentally measured UJS/ (N/mm^2)
UJS	L_{A1}-L_{B3}-L_{C1}-L_{D1}	780.85

TABLE X
SUMMARY OF THE RESULTS

Output quality characteristic	Theoretically calculated UJS /(N/mm^2)	Experimentally measured UJS /(N/mm^2)
UJS	791.60	780.85

Table X reveals that the experimentally measured and verified value is a little less than that of theoretically calculated UJS. However, both are closer to the ultimate tensile strength (800 N/mm^2) of the parent material (UNS S32750).

VI. CONCLUSION

The verification experiment reveals that the 'parameter design' methodology shown in the suggested ERDA approach provides a UJS value closer to the ultimate tensile strength of the parent metal. Hence, it is possible to conclude that the ERDA approach provides the means to estimate the DSS welding parameter levels that provide optimal joint performance. In addition, the suggested mathematical framework enables engineers and managers to use the RDA efficiently and effectively without spending much time familiarizing themselves with the approach. Consequently, it is possible to deploy the suggested approach for developing welding procedure specifications.

Future studies should be carried out to determine a formal mechanism to establish control factor levels using an expert system.

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