Analyses of hybrid Taguchi methods for optimization of submerged arc weld

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Abstract: In the present work, an attempt has been made to search an optimal process environment, capable of producing desired high quality submerged arc weldment. The optimal process environment consists of several process control parameters called factors. In this paper, four process variables viz. voltage (OCV), wire feed rate, traverse speed and electrode stick-out have been considered. Taguchi's L_{25} Orthogonal Array (OA) has been adopted for conducting experiments to produce bead-on-plate weld on mild steel plates. Four bead geometry parameters: depth of penetration, reinforcement, bead width and percentage dilution have been chosen as objective functions. These individual objective functions have been accumulated to calculate an overall quality indicator; which has been optimized finally. The aim was to convert a multi-objective optimization problem towards a single objective function, with the goal to optimize it. Two hybrid techniques, firstly, Taguchi method coupled with grey relational analysis; and secondly, Taguchi method in combination with Desirability Function (DF) approach has been applied. Comparison has been made on aforesaid two hybrid optimization techniques. Relative advantages as well as disadvantages of these techniques have been highlighted too. Optimal results have been verified through additional experiments; showed satisfactory results. Sensitivity analysis has been carried out to visualize the sensitiveness of the individual response weightages as well as the index of desirability function, influencing the optimal setting with the aim to satisfy varying requirements of different quality characteristics of the weld bead geometry.

Key words: Orthogonal Array (OA), Taguchi method, grey relational analysis, Desirability Function (DF)

1. Introduction

It is well known that several process control parameters influence weld bead geometry, bead quality and joint performance of submerged arc welding. These parameters should be selected in a judicious manner to reach the desired target or objective dictated by the area of application of the weldment. This can be achieved by multiple objective optimizations of the weldment.

Literature depicts that previous work has been explored in huge amount on various aspects of modeling, simulation and process optimization in submerged arc welding. The common approaches to tackle modeling and optimization problem in welding include multiple regression analysis, Response Surface Methodology (RSM) [Murugan, N. and Gunaraj, V., (2005)] and Artificial Neural Network (ANN). In most of the cases, the optimization has been performed using single objective function. For a multi-response process, while applying the optimal setting of control factors, it can be observed that, an increase/improvement of one response may cause change in another response, beyond the acceptable limit. Thus, for solving multi-criteria optimization problem, it is advised to convert multiple objectives into an equivalent single objective function. This may be assumed as the representative of all the quality characteristics of the product, which needs to be optimized.

Genetic Algorithm (GA) and Fuzzy Logic are also found to be useful techniques to solve optimization problem in the field of welding. GA was essentially developed in 1980s to emulate the “survival for fittest” principle introduced by Charles Darwin in his theory of evolution. From this perspective and since optimization is analogous to fitness or the ability to survive real-world conditions, it makes good sense to apply GA approach for system improvement and process/product optimization-as mentioned by Al-Aomar, Reid (2002).

Fuzzy logic allows degrees of truthfulness that measures to what extent a given object is included in a fuzzy set. Fuzzy sets correspond to linguistic variables used in a human language, [Wang, Jen-Ting and Jean, Ming-Der (2006)]. Xue, Y. *et al.* (2005) reported the possibilities of the fuzzy regression method in modeling the bead width in the robotic arc-welding process. In their paper, they developed a model for proper prediction of the process variables for obtaining the optimal bead width.

The welding researchers have also used dual response approach, a method of determining the optimal process conditions - in consideration of both the mean value and variance of a characteristic. The study conducted by Kim, D. and Rhee, S. (2003) and (2004) focused on the definition and optimization of the objective function in the dual response approach applied to a Gas Metal Arc Welding (GMAW) process. The objective function was defined using the desirability function. In their work, first, the regression models of the mean value and standard deviation of the depth of penetration were induced through regression analysis. Subsequently, an optimization algorithm (Genetic Algorithm) based on the regression models and constraints were applied to evaluate the welding process parameters, which could generate the desired penetration with minimized variance. Sathiya, P., *et al.* (2004) proposed a method to decide near optimal settings of the process parameters using Genetic Algorithm to optimize weld quality in friction welding. Correia, D. S. *et al.* (2004) stated about the possibility of using Genetic Algorithm as a method to decide near-optimal parameter setting of a GMAW process. Three control parameters namely welding voltage, wire feed rate and welding speed, and four quality responses viz. deposition efficiency, bead width, depth of penetration and reinforcement were considered in the study. The search for the near-optimal parameter setting was carried out step by step, with the GA predicting the next experiment based on the previous, and without knowledge of the modeling equations between the inputs and outputs of the GMAW process. It was found that GA was able to locate near-optimal conditions, with a relatively small number of experiments.

Another approach for optimization is the Controlled Random Search Algorithm (CRS), developed by Price, W. L. (1977). Kim, D. *et al.* (August 2005) applied the CRS algorithm to determine the welding process parameters by which the desired weld bead geometry could be obtained for Gas Metal Arc (GMA) welding. In this method, the output variables like front bead height; back bead width and penetration were determined by the input variables namely wire feed rate, welding voltage and welding speed. They proposed an objective function formulated by using the front bead height, back bead width and penetration affecting the weld quality. As per the proposed formulation of the objective function, the optimal welding parameters would be determined by minimization of that function.

Optimization using desirability function (DF) approach is also very helpful in this context. Asiabanpour, B. *et al.* (2004), Ful-Chiang, Wu. (2005) used this approach in their research work. This approach converts each of the responses (objectives) into their individual desirability value, which may vary from zero to one. If the response value is beyond the acceptable range, the desirability is assumes zero. If it reaches the target, desirability value becomes one. Corresponding to each objective, the individual desirability values are then accumulated to compute the overall or composite desirability function. The common trend is to develop a mathematical model of the composite desirability, in which it is represented as a function of process variables. Optimization is then performed to reveal factors combination to achieve maximum overall desirability.

Taguchi's philosophy is an efficient tool for the design of high quality manufacturing system, [Unal, R. and Dean, Edwin B., (1991), Rowlands, H., *et al.* 2000, Antony, J. and Antony, F., (2001), Maghsoodloo, S. *et al.* (2004)]. It can reveal optimal setting by conducting limited number of experiments. However, Taguchi method alone cannot solve multi-objective optimization problem, Jeyapaul, R. *et al.* (2005). Therefore, Taguchi method coupled with grey relational analysis is the appropriate option; found by previous researchers.

In grey based Taguchi method, a multiple response process optimization problem can be converted to a single response optimization problem where overall grey relational grade serves as the single objective function or response function to be optimized (maximized).
Tarng, Y. S. *et al.* (2002) applied grey-based Taguchi methods for optimization of Submerged Arc Welding process parameters in hardfacing. They considered multiple weld qualities and determined optimal process parameters based on grey relational grade from grey relational analysis proposed by Taguchi method.

Apart from grey-Taguchi, application of other hybrid techniques deserves mention. These techniques are: - (i) Taguchi method coupled with fuzzy logic, (ii) Genetic Algorithm and fuzzy logic, (iii) Genetic Algorithm in combination with Response Surface Methodology, and (iv) Taguchi-Genetic Algorithm [Tsai, Jinn-Tsong (August 2004)].

Tarng, Y. S. *et al.* (July 2000) applied fuzzy logic in the Taguchi method to optimize the submerged arc welding process with multiple performance characteristics. An orthogonal array, the signal-to-noise ratio, multi-response performance index and Analysis of Variance (ANOVA) were employed to study the performance characteristics in the submerged arc welding process. The process parameters, namely arc current, arc voltage, welding speed, electrode protrusion and preheat temperature were optimized with considerations of the performance characteristics, including deposition rate and dilution. Experimental results were provided to confirm the effectiveness of this approach. Kim, D. *et al.* (2002) suggested a Genetic Algorithm (GA) and Response Surface Methodology (RSM) for determining optimal welding conditions of a GMA welding process. First, in a relatively broad region, near-optimal conditions were determined through a Genetic Algorithm. Then, the optimal conditions for welding were evaluated by the investigators over a relatively small region around these near-optimal conditions by using Response Surface Methodology.

Aforesaid review highlights that, apart from GA, fuzzy-logy, RSM; hybrid Taguchi techniques have been widely used for multi-criteria optimization in the field of welding. In grey-Taguchi technique, grey relational analysis is generally used only to evaluate a multi-quality indicator. Desirability function approach does the same thing. It converts individual desirability values into an overall desirability function. So, it is felt that grey-Taguchi method can be replaced by Taguchi-desirability method. It has been observed that in case of solving multi-objective optimization problem using hybrid Taguchi techniques; there are several variables which have to be predefined while solving the optimization problem. For example, in grey-Taguchi technique, all the responses may or may not be of equal importance. So, different weightages have to be assigned to different responses, according to their preference. Therefore, in grey-Taguchi technique individual response weightages may be considered as variable parameters. Similarly, in desirability function approach, the index of desirability function can be selected and varied, within a given range, according to the consideration of the design optimizer. Moreover, while calculating the overall desirability value, individual responses may be assigned to different weightages. It is felt that, variation of aforesaid parameters my have predominant effect on the optimal setting; which needs to be investigated.

Therefore, apart from comparing optimal results and highlighting application feasibility of (a) grey-Taguchi and (b) Taguchi-desirability techniques, the present work also aims at evaluating the sensitivity of the response weightages as well as desirability function indexes on section of the optimal setting.

2. Taguchi method

Taguchi's philosophy, developed by Dr. Genichi Taguchi, is an efficient tool for the design of high quality manufacturing system. It is a method based on Orthogonal Array (OA) experiments, which provides much-reduced variance for the experiment resulting optimum setting of process control parameters. Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental runs), and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output; serve as objective functions in the optimization process. This technique helps in data analysis and prediction of optimum results. In order to evaluate optimal parameter settings, Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio takes both the mean and the variability into account. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/process to be optimized. The standard S/N ratios generally used are as follows: - Nominal-is-Best (NB), lower-the-better (LB) and Higher-the-Better (HB). The optimal setting is the parameter combination, which has the highest S/N ratio.

3. Grey relational analysis

In grey relational analysis, experimental data i.e. measured features of quality characteristics of the product are first normalized ranging from zero to one. This process is known as grey relational generation. Next, based on normalized experimental data, grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. Then overall grey relational grade is determined by averaging the grey relational coefficient corresponding to selected responses. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade. This approach converts a multiple- response- process optimization problem into a single response optimization situation, with the objective function is overall grey relational grade. The optimal parametric combination is then evaluated by maximizing the overall grey relational grade.

In grey relational generation, the normalized data corresponding to lower-the-better (LB) criterion can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{a}$$

For higher-the-better (HB) criterion, the normalized data can be expressed as:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{b}$$

Where $x_i(k)$ is the value after the grey relational generation, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for the kth response. An ideal sequence is $x_0(k)$ for the responses. The purpose of grey relational grade is to reveal the degrees of relation between the sequences say, $[x_0(k) \ and \ x_i(k), i = 1,2,3.......,25]$. The grey relational coefficient $\xi_i(k)$ can be calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \tag{c}$$

Here $\Delta_{0i} = \|x_0(k) - x_i(k)\|$ = difference of the absolute value $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient $0 \le \psi \le 1$; $\Delta_{\min} = \forall j^{\min} \in i \forall k^{\min} \|x_0(k) - xj(k)\| =$ the smallest value of Δ_{0i}; and $\Delta_{\max} = \forall j^{\max} \in i \forall k^{\max} \|x_0(k) - xj(k)\| =$ largest value of Δ_{0i}. After averaging the grey relational coefficients, the grey relational grade γ_i can be computed as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad \text{(d)}$$

Where $n =$ number of process responses. The higher value of grey relational grade corresponds to intense relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence. Therefore, higher grey relational grade means that the corresponding parameter combination is closer to the optimal.

4. Desirability function approach

Individual desirability values related to each of bead geometry parameters have been calculated using the formula proposed by Derringer and Suich, (1980). For bead width, reinforcement, area of reinforcement and bead volume Lower-the-better (LB); and for depth of penetration, area of penetration and dilution percentage Higher-the-better (HB) criterion has been selected.
Individual desirability value using Lower-the-better (LB) criterion is shown in *Appendix* (Figure A). The value of $\hat{y}$ is expected to be the lower the better. When $\hat{y}$ is less than a particular criteria value, the desirability value d_i equals to 1; if $\hat{y}$ exceeds a particular criteria value, the desirability value equals to 0. d_i can vary within 0 to 1. The desirability function of the Lower-the-better (LB) criterion can be written as below (equations e to g). Here, $y_{\min}$ denotes the lower tolerance limit of $\hat{y}$, the $y_{\max}$ represents the upper tolerance limit of $\hat{y}$ and r represents the desirability function index, which is to be assigned previously according to the consideration of the optimization solver. If the corresponding response is expected to be closer to the target, the index can be set to the larger value, otherwise a smaller value.

$$\text{If } \hat{y} \le y_{\min},\ d_i = 1 \quad \text{(e)}$$

$$\text{If } y_{\min} \le \hat{y} \le y_{\max},\ d_i = \left(\frac{\hat{y} - y_{\max}}{y_{\min} - y_{\max}}\right)^r \quad \text{(f)}$$

$$\text{If } \hat{y} \ge y_{\max},\ d_i = 0 \quad \text{(g)}$$

Individual desirability value using Higher-the-better (HB) criterion is shown in *Appendix* (Figure B). The value of $\hat{y}$ is expected to be the higher the better. When $\hat{y}$ is exceeds a particular criteria value, according to the requirement, the desirability value d_i equals to 1; if $\hat{y}$ is less than a particular criteria value, i.e. less than the acceptable limit, the desirability value equals to 0. The desirability function of the Higher-the-better (HB) criterion can be written as below (equations h to j). Here, $y_{\min}$ denotes the lower tolerance limit of $\hat{y}$, the $y_{\max}$ represents the upper tolerance limit of $\hat{y}$ and r represents the desirability function index, which is to be assigned previously according to the consideration of the optimization solver. If the corresponding response is expected to be closer to the target, the index can be set to the larger value, otherwise a smaller value.

If $\hat{y} \le y_{\min}$, $d_i = 0$ (h)

If $y_{\min} \le \hat{y} \le y_{\max}$, $d_i = \left(\dfrac{\hat{y} - y_{\min}}{y_{\max} - y_{\min}} \right)^r$ (i)

If $\hat{y} \ge y_{\max}$, $d_i = 1$ (j)

The individual desirability values have been accumulated to calculate the overall desirability, using the following equation (k). Here D is the overall desirability value, d_i is the individual desirability value of ith quality characteristic and n is the total number of responses.

$$D = (d_1 d_2 .... d_n)^{\frac{1}{n}} \quad \text{(k)}$$

5. Experiment

Bead-on-plate SAW welding on mild steel plates (thickness 10 mm) has been carried out as per Taguchi's L_{25} OA design with 25 combinations of voltage (OCV), wire feed rate, traverse speed and electrode stick-out. Copper coated electrode wire of diameter 3.16 mm (AWS A/S 5.17:EH14) has been used during the experiments. Welding has been performed with flux (AWS A5.17/SFA 5.17) with grain size 0.2 to 1.6 mm with basicity index 1.6 (Al_2O_3+MnO_2 35%, CaO+MgO 25% and SiO_2+TiO_2 20% and CaF_2 15%). The experiments have been performed on Submerged Arc Welding Machine- INDARC AUTOWELD MAJOR (Maker: IOL Ltd., India). Weld being made, the specimens have been prepared for metallographic test. Features of bead geometry (macrostructure, Figure C in *Appendix*) have been observed in Optical Trinocular Metallurgical Microscope (Make: Leica, GERMANY, Model No. DMLM, S6D & DFC320 and Q win Software). The domain of experimentation is shown in Table 1. The design of experiment and collected experimental data related to individual quality indicators of bead geometry have been listed in Table 2 and Table 3 respectively.

Table 1: Process control parameters and their limits

Parameters	Units	Notation	1	2	3	4	5
Voltage (OCV)	Volts	V	25	27	28	29	31
Wire feed rate	cm/min	Wf	340	655	970	1285	1600
Traverse speed	cm/min	Tr	46	72	98	124	150
Stick-out	mm	N	25	27	29	31	33

Table 2: Taguchi's L25 Orthogonal Array (OA) design

Sl. No.	V	Wf	Tr	N
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	1	5	5	5
6	2	1	2	3
7	2	2	3	4
8	2	3	4	5
9	2	4	5	1
10	2	5	1	2
11	3	1	3	5
12	3	2	4	1
13	3	3	5	2
14	3	4	1	3
15	3	5	2	4
16	4	1	4	2
17	4	2	5	3
18	4	3	1	4
19	4	4	2	5
20	4	5	3	1
21	5	1	5	4
22	5	2	1	5
23	5	3	2	1
24	5	4	3	2
25	5	5	4	3

Table 3: Experimental data related to features of bead geometry

Sl. No.	Penetration (mm)	Reinforcement (mm)	Bead width (mm)	Dilution (%)
1	4.1970	2.2773	9.1647	35.3825
2	3.8740	1.6683	9.8077	41.9825
3	3.8475	1.5475	9.8975	43.2125
4	3.9110	1.5493	9.8327	43.0625
5	4.3080	1.9203	9.2398	38.6225
6	3.4545	1.4183	9.7800	41.1875
7	3.4755	1.2705	10.1497	44.1950
8	3.5285	1.2780	10.0600	42.2200
9	3.3670	1.4667	8.8767	47.3125
10	4.9320	2.4087	13.9917	46.7725
11	3.2985	1.2280	10.1127	39.5975
12	3.2430	1.1878	9.9132	46.8300
13	3.2500	1.3325	8.6950	44.8250
14	4.1605	1.9793	14.7075	45.4525
15	4.3830	1.7803	12.6232	46.9700
16	3.1750	1.1163	9.7482	41.5325
17	3.1925	1.2717	8.7850	42.0325
18	3.8205	1.7940	15.7650	43.5350
19	3.7450	1.4048	13.6882	42.7625
20	4.1795	1.8085	11.5528	54.0250
21	3.3450	1.3317	9.3967	34.6525
22	3.5500	1.6557	18.7718	37.7525
23	3.5285	1.5340	15.0150	48.6350
24	3.6315	1.4625	13.6247	47.9050
25	4.0525	1.7582	12.0500	47.0425

6. Optimization using grey-Taguchi method

Experimental data, as per Taguchi's L_{25} OA design, (Table 3) have been normalized first as discussed in section 3. The normalized experimental data are shown in Table 4. For depth of penetration and dilution, LB; and for reinforcement and bead width LB criteria have been chosen. Quality loss estimates (Δ_{0i}) related to individual features of bead geometry have been furnished in Table 5. Then grey relational coefficients for each quality characteristics have been calculated using equation (c); and they are furnished in Table 6. In this study, distinguishing coefficient has been assumed as $\phi = 0.5$. Calculated grey relational coefficients for individual responses have been accumulated to evaluate the overall grey relational grade using equation (d), which is the representative of the multi-quality features of bead geometry; with the assumption that quality features are equally important all responses have same weightage value). The calculated overall grey relational grades for each experimental runs have been shown in Table 6.

Table 4: Data preprocessing of each performance characteristics (Grey relational generation)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution
1	0.5817	0.1017	0.9534	0.0377
2	0.3978	0.5729	0.8896	0.3784
3	0.3828	0.6664	0.8807	0.4419
4	0.4189	0.6650	0.8871	0.4341
5	0.6448	0.3779	0.9459	0.2049
6	0.1591	0.7663	0.8923	0.3373
7	0.1710	0.8807	0.8556	0.4926
8	0.2012	0.8749	0.8645	0.3906
9	0.1093	0.7289	0.9820	0.6535
10	1.0000	0.0000	0.4744	0.6256
11	0.0703	0.9136	0.8593	0.2553
12	0.0387	0.9447	0.8791	0.6286
13	0.0427	0.8327	1.0000	0.5251
14	0.5609	0.3323	0.4033	0.5575
15	0.6875	0.4862	0.6102	0.6358
16	0.0000	1.0000	0.8955	0.3551
17	0.0100	0.8798	0.9911	0.3810
18	0.3674	0.4756	0.2984	0.4585
19	0.3244	0.7768	0.5045	0.4186
20	0.5717	0.4644	0.7164	1.0000
21	0.0968	0.8333	0.9304	0.0000
22	0.2134	0.5826	0.0000	0.1600
23	0.2012	0.6768	0.3728	0.7218
24	0.2598	0.7321	0.5108	0.6841
25	0.4994	0.5033	0.6671	0.6396

Table 5: Calculation of quality loss estimates (Δ_{0i})

Sl. No.	Penetration	Reinforcement	Bead width	Dilution
1	0.4183	0.8983	0.0466	0.9623
2	0.6022	0.4271	0.1104	0.6216
3	0.6172	0.3336	0.1193	0.5581
4	0.5811	0.3350	0.1129	0.5659
5	0.3552	0.6221	0.0541	0.7951
6	0.8409	0.2337	0.1077	0.6627
7	0.8290	0.1193	0.1444	0.5074
8	0.7988	0.1251	0.1355	0.6094
9	0.8907	0.2711	0.0180	0.3465
10	0.0000	1.0000	0.5256	0.3744
11	0.9297	0.0864	0.1407	0.7447
12	0.9613	0.0553	0.1209	0.3714
13	0.9573	0.1673	0.0000	0.4749
14	0.4391	0.6677	0.5967	0.4425
15	0.3125	0.5138	0.3898	0.3642
16	1.0000	00.0000	0.1045	0.6449
17	0.9900	0.1202	0.0089	0.6190

18	0.6326	0.5244	0.7016	0.5415
19	0.6756	0.2232	0.4955	0.5814
20	0.4283	0.5356	0.2836	0.0000
21	0.9032	0.1667	0.0696	1.0000
22	0.7866	0.4174	1.0000	0.8400
23	0.7988	0.3232	0.6272	0.2782
24	0.7402	0.2679	0.4892	0.3159
25	0.5006	0.4967	0.3329	0.3604

Table 6: Individual grey relational coefficients and overall grey relational grade

Sl. No.	Grey relational coefficients of individual responses				Overall grey relational grade
	Penetration	Reinforcement	Bead width	Dilution	
1	0.5445	0.3576	0.9147	0.3419	0.5397
2	0.4536	0.5393	0.8191	0.4458	0.5645
3	0.4475	0.5998	0.8074	0.4725	0.5818
4	0.4625	0.5988	0.8158	0.4691	0.5866
5	0.5847	0.4456	0.9024	0.3861	0.5797
6	0.3729	0.6815	0.8228	0.4300	0.5768
7	0.3762	0.8074	0.7759	0.4963	0.6140
8	0.3850	0.7999	0.7868	0.4507	0.6056
9	0.3595	0.6484	0.9653	0.5907	0.6410
10	1.0000	0.3333	0.4875	0.5718	0.5981
11	0.3497	0.8527	0.7804	0.4017	0.5961
12	0.3422	0.9004	0.8053	0.5738	0.6554
13	0.3431	0.7493	1.0000	0.5129	0.6513
14	0.5324	0.4282	0.4559	0.5305	0.4868
15	0.6154	0.4932	0.5619	0.5786	0.5623
16	0.3333	1.0000	0.8271	0.4367	0.6493
17	0.3356	0.8062	0.9825	0.4468	0.6428
18	0.4415	0.4881	0.4161	0.4801	0.4564
19	0.4253	0.6914	0.5023	0.4624	0.5203
20	0.5386	0.4828	0.6381	1.0000	0.6649
21	0.3563	0.7500	0.8778	0.3333	0.5794
22	0.3886	0.5450	0.3333	0.3731	0.4100
23	0.3850	0.6074	0.4436	0.6425	0.5196
24	0.4032	0.6511	0.5055	0.6128	0.5432
25	0.4997	0.5017	0.6003	0.5811	0.5457

Thus, the multi-criteria optimization problem has been transformed into a single objective optimization problem using the combination of Taguchi approach and grey relational analyses. Higher is the value of grey relational grade, the corresponding factor combination is said to be close to the optimal.

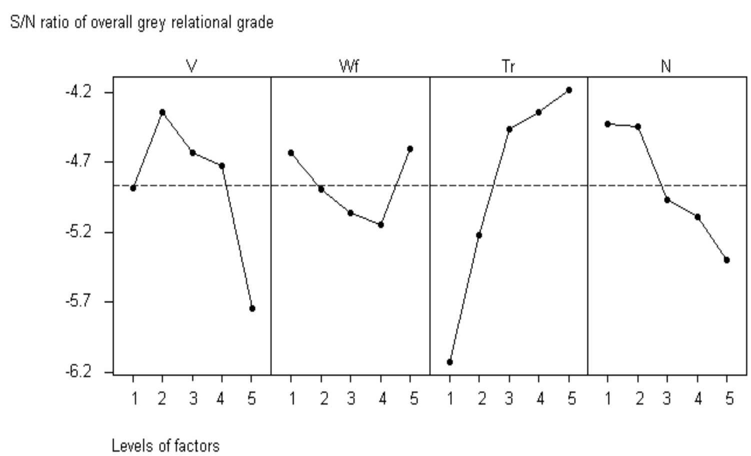

Figure 1: S/N ratio plot of overall grey relational grade

The S/N ratio plot for the overall grey relational grade is represented graphically in Figure 1. The S/N ratio for overall grey relational grade has been calculated using HB (higher-the-better) criterion (equation l).

$$SN\,(Higher-the-better) = -10\log\left[\frac{1}{t}\sum_{i=1}^{t}\frac{1}{y_i^2}\right] \tag{l}$$

Where t is the number of measurements, and y_i the measured $i\,th$ characteristic value i.e. $i\,th$ quality indicator. With the help of the Figure 1, optimal parametric combination has been determined. The optimal factor setting becomes **V2 Wf5 Tr5 N1**.

ANOVA of overall grey relational grade (Table 7) is important to estimate the level of significance and order of significance of the controllable factors influencing overall quality index (grey relational grade in the present case) of the bead geometry. In ANOVA, P-value is determined which is termed as probability of significance. If P-value for a factor becomes less than 0.05; then it can be concluded that, the factorial influence is significant on the response parameter (95% confidence level). ANOVA of overall grey relational grade has revealed that the important factors influencing overall grey relation grade are traverse speed, voltage, stick-out and wire feed rate; in their order to significance.

Table 7: Analysis of variance (ANOVA) of overall grey relational grade

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	4	0.0224833	0.0224833	0.0056208	11.12	0.002
Wf	4	0.0046650	0.0046650	0.0011662	2.31	0.146
Tr	4	0.0513018	0.0513018	0.0128254	25.38	0.000
N	4	0.0145281	0.0145281	0.0036320	7.19	0.009
Error	8	0.0040430	0.0040430	0.0005054		
Total	24	0.0970211				

DF=Degree of freedom, SS= Sum of squared deviation; MS=Mean squared deviation, F=Fisher's F ratio; P=Probability of significance

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. Table 8 reflects the satisfactory result of confirmatory experiment.

Table 8: Results of confirmatory experiment

	Optimal setting	
	Prediction	Experiment
Level of factors	**V2 Wf5 Tr5 N1**	**V2 Wf5 Tr5 N1**
S/N ratio of Overall grey relational grade	-2.95468	-3.130
Overall grey relational grade	0.7124	0.6974

7. Sensitivity analysis in grey-Taguchi method

In the aforesaid study, it has been assumed that all quality features are equally important. But in practical case, it may not be so. Depending on the area of application, different response may have different preference and tolerance limit. For example, among the bead geometry parameters, considered in the present case i.e. bead width, reinforcement, depth of penetration and dilution; the important responses are penetration depth and percentage dilution. These two have to be controlled precisely and maximized to increase joint strength. In this context, bead width and reinforcement are not so important. Therefore, different weightages have to be assigned to different responses. Much weightages should be given to penetration and dilution. Less weightage should be for reinforcement and bead width.

In this section, sensitivity analysis has been carried out to observe whether the optimal setting is sensitive to the individual response weightages. That means, if, there is any change in optimal setting due to change in relative weightages of the responses; it can be concluded that the optimal setting is sensitive to the individual weightage values. In this section, different weightages have been assigned to different bead geometry parameters. Results of sensitivity analysis have been presented below in tabular form (Table 9). The equation for calculating overall grey relational grade (with different weightages for different responses) is shown below:

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

Here, γ_i is the overall grey relational grade for ith experiment. $\xi_i(k)$ is the grey relational coefficient of kth response in ith experiment and w_k is the weightage assigned to the kth response.

Table 9: Results of sensitivity analysis

	Case 1	Case 2	Case 3	Case 4	Case 5
Penetration weight age	0.4	0.5	0.4	0.2	0.7
Reinforcement weight age	0.1	0.05	0.05	0.05	0.05
Bead width weight age	0.1	0.05	0.05	0.05	0.05
Dilution weight age	0.4	0.4	0.5	0.7	0.2
Optimal setting	V2 Wf5 Tr3 N1	V2 Wf5 Tr1 N1	V2 Wf5 Tr3 N1	V2 Wf5 Tr3 N1	V2 Wf5 Tr1 N2
S/N ratio of Overall grey relational grade	-2.70654	-2.71561	-2.41340	-2.41340	-2.27419
Overall grey relational grade	0.7323	0.7315	0.7574	0.7574	0.7696
ANOVA result	Wf (P=0.001) N(P=0.020)	Wf (P=0.001) N(P=0.045)	Wf (P=0.000) N(P=0.015)	Wf (P=0.001) N(P=0.005)	Wf(P=0.002)

8. Optimization using desirability function and Taguchi method

In this part of the present work, multi-response optimization problem has been considered and solved to arch of an optimal parametric combination to yield favorable bead geometry of submerged arc bead-on-plate weldment on mild steel. Taguchi's L_{25} Orthogonal Array (OA) design has been used to derive objective functions, which need to be optimized within experimental domain. The objective functions have been selected in relation to parameters of bead geometry viz. bead width, reinforcement, depth of penetration and dilution. Taguchi optimization technique followed by desirability function approach has been applied to solve this multi-response optimization problem.

Individual desirability values have been calculated using equations (e) to (g) for LB and (h) to (j) for HB criterion. For bead width and reinforcement, LB and for depth of penetration and dilution, HB criteria have been chosen. These individual desirability values of the responses have been accumulated to convert overall desirability value. These have been furnished in Table 10. In this study the desirability function index has been assumed as $r = 1$.

Table 10: Calculation of desirability value ($r = 1$)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution	Overall desirability
1	0.5817	0.1017	0.9534	0.0377	0.2147
2	0.3978	0.5729	0.8896	0.3784	0.5263
3	0.3828	0.6664	0.8807	0.4419	0.5613
4	0.4189	0.6650	0.8871	0.4341	0.5723
5	0.6448	0.3779	0.9459	0.2049	0.4662
6	0.1591	0.7663	0.8923	0.3373	0.4377
7	0.1710	0.8807	0.8556	0.4926	0.5019
8	0.2012	0.8749	0.8645	0.3906	0.4938
9	0.1093	0.7289	0.9820	0.6535	0.4755
10	1.0000	0.0000	0.4744	0.6256	0.0000
11	0.0703	0.9136	0.8593	0.2553	0.3445
12	0.0387	0.9447	0.8791	0.6286	0.3770
13	0.0427	0.8327	1.0000	0.5251	0.3696
14	0.5609	0.3323	0.4033	0.5575	0.4525
15	0.6875	0.4862	0.6102	0.6358	0.6001
16	0.0000	1.0000	0.8955	0.3551	0.0000
17	0.0100	0.8798	0.9911	0.3810	0.2401
18	0.3674	0.4756	0.2984	0.4585	0.3932
19	0.3244	0.7768	0.5045	0.4186	0.4803
20	0.5717	0.4644	0.7164	1.0000	0.6604
21	0.0968	0.8333	0.9304	0.0000	0.0000
22	0.2134	0.5826	0.0000	0.1600	0.0000
23	0.2012	0.6768	0.3728	0.7218	0.4375
24	0.2598	0.7321	0.5108	0.6841	0.5077
25	0.4994	0.5033	0.6671	0.6396	0.5723

The composite desirability value being calculated, the next step is to maximize it. The optimal process condition can be evaluated by searching the specific parametric combination that can result maximum overall desirability value (close to 1). From Table 10, it has been seen that for some factor combinations (Sl. No. 10, 16, 21 and 22) the overall desirability became zero. In that case Taguchi's S/N ratio cannot be calculated. To overcome this, analyses have been made using mean of overall desirability value. Based on analysis of mean value, Taguchi method results Figure 2.

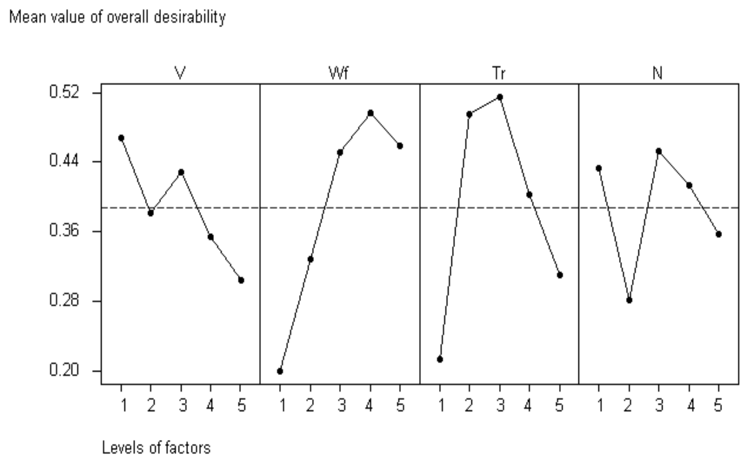

Figure 4: Graph for evaluation of optimal parametric combination (Mean plot of overall desirability)

From Figure 2, the optimal parametric combination has been evaluated. The optimal setting for maximum overall desirability becomes ***V1 Wf 4 Tr 3 N 3***. After optimization being done, the next step is to verify the optimal result. Confirmatory experiment has been conducted to verify optimal result (Table 11). ANOVA of the overall desirability is shown in Table 12.

Table 11: Results of confirmatory experiment

	Optimal setting	
	Prediction	Experiment
Level of factors	**V1 Wf 4 Tr 3 N 3**	**V1 Wf 4 Tr 3 N 3**
Penetration		4.0750
Reinforcement		1.6245
Bead width		10.1100
Dilution		44.3575
Overall desirability	0.771572	0.687420

Table 12: Analysis of variance (ANOVA) of overall desirability

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	4	0.08182	0.08182	0.02046	1.04	0.444
Wf	4	0.30105	0.30105	0.07526	3.83	0.050
Tr	4	0.32565	0.32565	0.08141	4.14	0.042
N	4	0.09672	0.09672	0.02418	1.23	0.371
Error	8	0.15736	0.15736	0.01967		
Total	24	0.96260				

DF=Degree of freedom, SS= Sum of squared deviation; MS=Mean squared deviation, F=Fisher's F ratio; P=Probability of significance

9. Sensitivity analysis in Taguchi method coupled with desirability function

9.1. Effect of individual response weightages

In the foregoing study using Taguchi-desirability function method, it has been assumed that all bead geometry parameters are equally important. Therefore, same weightages have been assigned to all the responses. But while dealing with the responses, having different weightages, the equation for calculating overall desirability changes to some extent compared to equation (k). In that case, the expression for overall desirability becomes:

$$D = [d_1^{w_1}.d_2^{w_2}..........d_n^{w_n}]^{\frac{1}{\sum w_n}} \qquad (n)$$

In order to investigate whether the optimal setting is sensitive to the response weightages, different weightages have been assigned to different responses. Overall desirability values have been calculated using equation (n). Taguchi method has been applied for evaluation of optimal setting. Results of sensitivity analysis are furnished in Table 13.

Table 13: Results of sensitivity analysis

	Case A	Case B	Case C	Case D	Case E
Penetration weight age	0.4	0.5	0.4	0.2	0.7
Reinforcement weight age	0.1	0.05	0.05	0.05	0.05
Bead width weight age	0.1	0.05	0.05	0.05	0.05
Dilution weight age	0.4	0.4	0.5	0.7	0.2
Optimal setting	V1 Wf 5 Tr 3 N 3	V1 Wf 5 Tr 2 N 3	V1 Wf 5 Tr 3 N 3	V3 Wf4 Tr2 N 1	V1 Wf5 Tr2 N 4
Overall desirability	0.707148	0.715876	0.692316	0.756696	0.774116
(ANOVA result) Most significant factor	Wf (P=0.026)	Wf (P=0.026)	Wf (P=0.023)	Wf (P=0.017) Tr(P=0.048)	Wf (P=0.037)

9.2. Effect of the desirability function index

The choice of the desirability function index depends on the optimization solver. Change in index changes individual desirability values as well as the overall desirability. In this section, different indexes (0.1, 0.3, 3 and 10) have been selected to check the effect of function index on the optimal setting. Tables 14-17 represent the individual desirability values (corresponding to the responses) as well as the overall desirability value, for different values function index. Results of sensitivity analysis are shown in tabular form below (Table 18).

Table 14: Calculation of desirability value ($r = 0.1$)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution	Overall desirability
1	0.9473	0.7956	0.9952	0.7205	0.8574
2	0.9119	0.9458	0.9884	0.9074	0.9378
3	0.9084	0.9602	0.9874	0.9216	0.9439
4	0.9167	0.9600	0.9881	0.9199	0.9457
5	0.9571	0.9073	0.9945	0.8534	0.9265
6	0.8321	0.9737	0.9887	0.8970	0.9207

7	0.8381	0.9874	0.9845	0.9316	0.9334
8	0.8518	0.9867	0.9855	0.9103	0.9318
9	0.8014	0.9689	0.9982	0.9584	0.9284
10	1.0000	0.0000	0.9281	0.9542	0.0000
11	0.7668	0.9910	0.9850	0.8724	0.8989
12	0.7224	0.9943	0.9872	0.9546	0.9070
13	0.7295	0.9819	1.0000	0.9376	0.9053
14	0.9438	0.8957	0.9132	0.9432	0.9237
15	0.9632	0.9304	0.9518	0.9557	0.9502
16	0.0000	1.0000	0.9890	0.9017	0.0000
17	0.6307	0.9873	0.9991	0.9080	0.8669
18	0.9047	0.9284	0.8861	0.9250	0.9109
19	0.8935	0.9751	0.9339	0.9166	0.9293
20	0.9456	0.9262	0.9672	1.0000	0.9594
21	0.7917	0.9819	0.9928	0.0000	0.0000
22	0.8569	0.9474	0.0000	0.8326	0.0000
23	0.8518	0.9617	0.9060	0.9679	0.9206
24	0.8739	0.9693	0.9350	0.9627	0.9344
25	0.9329	0.9337	0.9603	0.9563	0.9457

Table 15: Calculation of desirability value ($r = 0.3$)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution	Overall desirability
1	0.8500	0.5037	0.9858	0.3740	0.6303
2	0.7584	0.8461	0.9655	0.7471	0.8248
3	0.7497	0.8853	0.9626	0.7827	0.8409
4	0.7703	0.8848	0.9647	0.7785	0.8458
5	0.8767	0.7468	0.9835	0.6216	0.7954
6	0.5761	0.9233	0.9664	0.7218	0.7805
7	0.5887	0.9626	0.9543	0.8086	0.8132
8	0.6181	0.9607	0.9573	0.7543	0.8092
9	0.5147	0.9095	0.9946	0.8802	0.8001
10	1.0000	0.0000	0.7995	0.8688	0.0000
11	0.4509	0.9732	0.9555	0.6639	0.7264
12	0.3770	0.9831	0.9621	0.8700	0.7463
13	0.3882	0.9466	1.0000	0.8243	0.7419
14	0.8407	0.7185	0.7616	0.8392	0.7883
15	0.8937	0.8055	0.8623	0.8730	0.8580
16	0.0000	1.0000	0.9674	0.7330	0.0000
17	0.2509	0.9623	0.9973	0.7486	0.6516
18	0.7405	0.8002	0.6957	0.7914	0.7558
19	0.7134	0.9270	0.8144	0.7701	0.8025
20	0.8456	0.7945	0.9048	1.0000	0.8830
21	0.4963	0.9468	0.9786	0.0000	0.0000
22	0.6292	0.8504	0.0000	0.5771	0.0000
23	0.6181	0.8895	0.7438	0.9068	0.7804
24	0.6674	0.9107	0.8175	0.8923	0.8160
25	0.8120	0.8139	0.8856	0.8745	0.8458

Table 16: Calculation of desirability value ($r = 3$)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution	Overall desirability
1	0.1968	0.0011	0.8666	0.0001	0.0117
2	0.0630	0.1880	0.7040	0.0542	0.1458
3	0.0561	0.2959	0.6830	0.0863	0.1769
4	0.0735	0.2940	0.6981	0.0818	0.1874
5	0.2681	0.0540	0.8464	0.0086	0.1013
6	0.0040	0.4500	0.7105	0.0384	0.0837
7	0.0050	0.6831	0.6264	0.1195	0.1264
8	0.0081	0.6697	0.6462	0.0596	0.1202
9	0.0013	0.3872	0.9469	0.2791	0.1074
10	1.0000	0.0000	0.1067	0.2449	0.0000
11	0.0003	0.7625	0.6345	0.0166	0.0394
12	0.0001	0.8430	0.6794	0.2484	0.0614
13	0.0001	0.5774	1.0000	0.1448	0.0538
14	0.1765	0.0367	0.0656	0.1733	0.0926

15	0.3250	0.1150	0.2272	0.2570	0.2161
16	0.0000	1.0000	0.7181	0.0448	0.0000
17	0.0000	0.6809	0.9734	0.0553	0.0000
18	0.0496	0.1076	0.0266	0.0964	0.0608
19	0.0341	0.4687	0.1284	0.0734	0.1108
20	0.1869	0.1002	0.3677	1.0000	0.2881
21	0.0009	0.5787	0.8053	0.0000	0.0000
22	0.0097	0.1978	0.0000	0.0041	0.0000
23	0.0081	0.3100	0.0518	0.3760	0.0836
24	0.0175	0.3924	0.1333	0.3201	0.1308
25	0.1246	0.1275	0.2968	0.2616	0.1874

Table 17: Calculation of desirability value ($r = 10$)

Sl. No.	Penetration	Reinforcement	Bead width	Dilution	Overall desirability
1	0.0044	0.0000	0.6204	0.0000	0.0000
2	0.0001	0.0038	0.3103	0.0001	0.0019
3	0.0001	0.0173	0.2806	0.0003	0.0035
4	0.0002	0.0169	0.3018	0.0002	0.0038
5	0.0124	0.0001	0.5736	0.0000	0.0000
6	0.0000	0.0698	0.3201	0.0000	0.0000
7	0.0000	0.2807	0.2103	0.0008	0.0000
8	0.0000	0.2627	0.2333	0.0001	0.0000
9	0.0000	0.0423	0.8336	0.0142	0.0000
10	1.0000	0.0000	0.0006	0.0092	0.0000
11	0.0000	0.4050	0.2195	0.0000	0.0000
12	0.0000	0.5660	0.2757	0.0096	0.0000
13	0.0000	0.1603	1.0000	0.0016	0.0000
14	0.0031	0.0000	0.0001	0.0029	0.0000
15	0.0236	0.0007	0.0072	0.0108	0.0060
16	0.0000	1.0000	0.3316	0.0000	0.0000
17	0.0000	0.2777	0.9142	0.0001	0.0000
18	0.0000	0.0006	0.0000	0.0004	0.0000
19	0.0000	0.0800	0.0011	0.0002	0.0000
20	0.0037	0.0005	0.0356	1.0000	0.0160
21	0.0000	0.1615	0.4859	0.0000	0.0000
22	0.0000	0.0045	0.0000	0.0000	0.0000
23	0.0000	0.0202	0.0001	0.0384	0.0000
24	0.0000	0.0442	0.0012	0.0224	0.0000
25	0.0010	0.0010	0.0174	0.0115	0.0038

Table 13: Results of sensitivity analysis of the desirability function index

	Case P	Case Q	Case R	Case S	Case T
Desirability function index	0.1	0.3	1	3	10
Optimal setting	V1 Wf 4 Tr 3 N 3	V1 Wf 4 Tr 3 N 3	V1 Wf 4 Tr 3 N3	V1 Wf 4 Tr 3 N 4	V4 Wf 5 Tr 3 N 1

10. Conclusions

1. Grey-Taguchi and desirability-Taguchi are two hybrid techniques, discussed above, can be used for solving multi-criteria optimization problem in submerged arc welding. Both the approaches first evaluate a composite quality indicator; which is finally optimized (maximized) to search the optimal process condition. In grey-Taguchi approach, the composite quality indicator is the overall grey relational grade. Whereas, in desirability-Taguchi approach, overall desirability function serves as composite quality indicator.
2. Two methods have the same purpose, but the way they derive the composite quality indicator differs. Grey-Taguchi is based on quality loss function. It minimizes quality loss i.e. on the contrary; it maximizes the inverse of quality loss. Grey relational coefficient is determined taking inverse function of quality loss. Therefore, the overall grey relational grade is inversely proportional to the cumulative quality loss due to multiple responses.

But, in case of Taguchi-desirability function method; it estimates to what extent individual responses are close to the target value or lie within acceptable limit. If a response attains its target value, which is highly desired, the corresponding desirability value becomes 100% i.e. 1. If the response is beyond the acceptable limit, which is not desired; the situation is tackled by assuming a desirability value 0% or simply zero. The overall desirability value is the combination of individual desirability values with the aim to maximize it.

3. Both the approaches finally yield to maximization of a single objective function, but each having its own individual objectives. One, to reduce quality loss and the other, to attain highest desirability. Therefore, results of optimization i.e. optimal setting determined by these two approaches differ.
4. Two approaches are based on their individual objectives; therefore, it is evident that the extent of significance of process control parameters should be different while influencing these two separate objectives. ANOVA on overall grey relational grade reveals that voltage (OCV), traverse speed and stick-out influence significantly the overall grey relational grade (Table 7); whereas, ANOVA on overall desirability estimates that wire feed rate and traverse speed affects the overall desirability significantly (Table 12).
5. In grey-Taguchi analysis, when all responses are equally important, wire feed rate has been found insignificant to influence overall grey relational grade. But it is observed that if response weightages are varied, wire feed rate exhibits significant influence.
6. Sensitivity analysis in grey-Taguchi method reveals that individual response weightages are not too much sensitive to the optimal setting. It has been observed that setting of voltage and wire feed rate need not to be varied to meet the different preferences of the different responses. At the same time, traverse speed and stick-out are not too much susceptible to the variation of individual factor weightages.
7. Desirability-Taguchi method reveals that, when all responses are equally important, wire feed rate has been found significant to influence overall desirability value. It is observed that if response weightages are varied, wire feed rate again exhibits significant influence.
8. Sensitivity analysis in desirability-Taguchi method reveals that individual response weightages are much sensitive to the optimal setting compared to the case of grey-Taguchi analysis.
9. Sensitivity analysis for the desirability function indexes in desirability-Taguchi method results that when desirability index is in the range $r \leq 1$, it is not sensitive to the optimal setting. But the situation reverses when $r > 1$. In that case desirability index has been found very sensitive.
10. Both the approaches can solve multi-objective optimization problem, but grey-Taguchi technique is simpler compared to Taguchi-desirability technique. Because, in desirability function approach lower limit/upper limit/target i.e. acceptable limits of the responses have to be known earlier. Based on the acceptable limit, appropriate desirability function is to be selected to calculate individual desirability values. Whereas, in grey-Taguchi method, individual grey relational coefficients are calculated based on HB or LB criterion (in some special case NB i.e. nominal the best, target value is known) without knowledge of acceptable limit for the responses. In that case, while applying the optimal result in practical case, it may so happen that the optimal setting cannot be used. For example, suppose penetration depth has been optimized using HB criterion. The idea is like that: more is the penetration depth; more will be the joint strength. But is practical case, the optimal setting for high penetration may yield burn out of the base metal. Therefore, it is advisable to search the optimal setting within feasible acceptable limits of the response variables. Desirability-Taguchi approach does the same thing.
11. Both the approaches can solve multi-objective optimization problem through a limited number of experiments. This saves experimentation cost as well as time. There is no need

for mathematical modeling of the overall quality indicator, which is required in RSM, GA methods.

12. Despite of relative advantages and disadvantages, aforesaid two hybrid Taguchi approaches have been found efficient. However, the response weightages, desirability function index, selection of important responses, which need to be give higher preference, all these depend on the previous experience, knowledge, skill and compromising attitude of the optimization solver.

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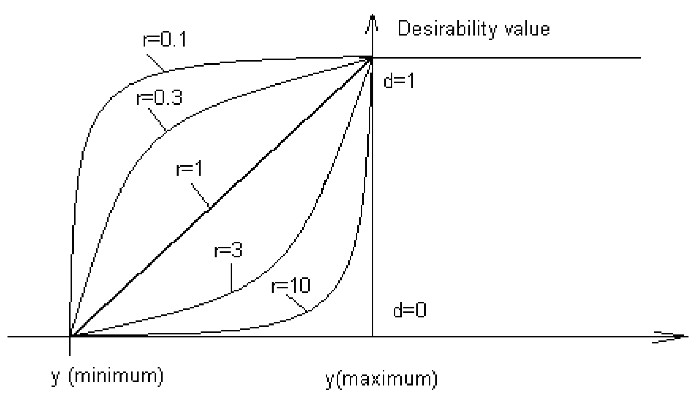
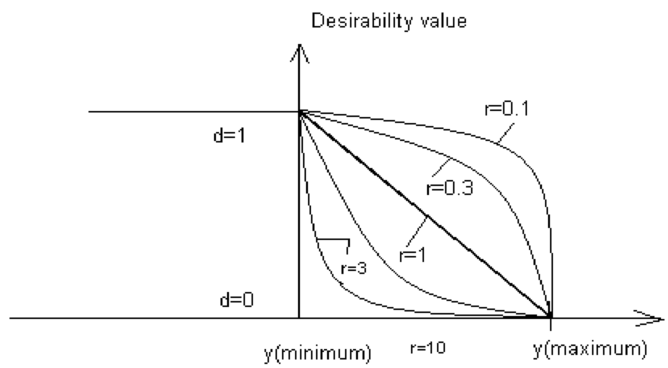


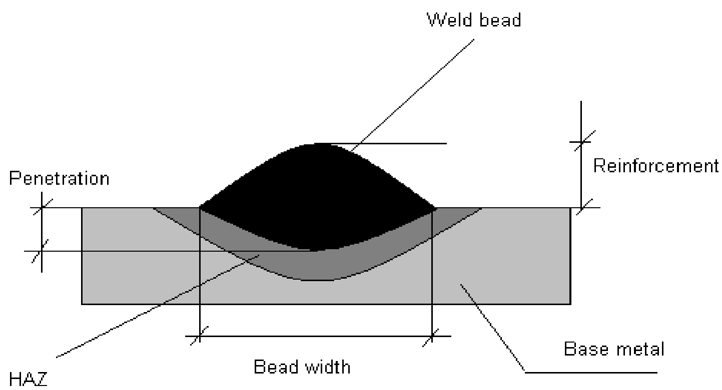
Desirability function (Higher-the-better)

APPENDIX (Figure A)



Desirability function (Lower-the-better)

APPENDIX (Figure B)



Features of bead geometry

APPENDIX (Figure C)