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Empirical modeling of shot peening parameters for welded austenitic stainless steel using grey relational analysis †

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Abstract

The attempt of this paper is to present an effective approach for the optimization of the shot peening process of welded AISI 304 austenitic stainless steel with multi performance characteristics using Grey relational analysis (GRA) based on Taguchi orthogonal array. Twenty-seven experimental runs are performed to determine best process parameters level. An analysis of variance (ANOVA) is carried out to identify significant peening parameters. The response tables are obtained for analyzing the optimal levels of shot peening parameters and major factors that affect the quality function. The multiple performance characteristics including tensile strength, surface hardness and surface roughness are the quality functions considered for the optimization. Further mathematical models are developed using regression analysis for the tensile strength, surface hardness and surface roughness. It will be very helpful to the engineers in deciding the levels of the shot peening parameters for desired performance characteristics.

Keywords: ANOVA; Gray relational analysis (GRA); Optimization; Shot peening; Taguchi method

1. Introduction

Shot peening is the process of inducing residual compressive stresses in the thin skin layer of surface by mechanical yielding. It is used in different components of automobiles, aircraft and railway industries like leaf spring, helical spring, gears, axle bearing, crankshafts, milling cutters, connecting rod, cylinder block, valve springs, washers etc. [1]. The major applications of the shot peening are related to improvement and restoration of properties and reliability of machine elements by increasing their surface hardness, tensile strength, surface finish, impact strength, fatigue strength etc. [2, 3]. The improvement of properties depends on the intensity of shot peening process. The intensity can be varied by regulating the size of shot, the hardness of shot, the speed at which was fired, the length of time, the distance of nozzle from the surface and the work exposed to the shot. The interaction of material properties with the shot peening parameters, results in the generation of residual compressive stress in the thin skin layer of the weld surface, changes the microstructure and substructure of material, changes the surface conditions and hardening characteristics.

Stainless steel can be welded by most of the common arc welding processes i.e. flux cored arc welding, gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW) with coated electrodes and submerged arc welding (SAW). The cost of stainless steel is approximately six times more than that of mild steel. That's why, it is important that the proper electrodes or filler metals are selected and the proper welding procedures are followed to minimize rework or scrap losses due to faulty welds. E-308 electrodes are used to weld AISI 304 austenitic stainless steel [4-6].

The controlled shot peening parameters helps in enhancing the mechanical and surface properties of the material. The improvement of these properties by shot peening and other plastic deformation treatment are mainly due to ability of the residual stresses in stopping the microcrack propagation and forming higher dislocation densities near the surface [7]. Dorr et al. and Obata et al. have discussed the increase in surface hardness and surface roughness with increase in shot size and the peening intensity [8, 9]. The shot peening variables like shot material, shot quality, shot intensity, shot coverage etc. affect the mechanical and surface properties. Prakash et al. have studied shot peening on steels results in high strength to weight ratio [10]. As per the guidelines given by Champaine [11], the exposure time is an important factor to achieve desired peening coverage for the material.

Only a few authors have used the design of experiment

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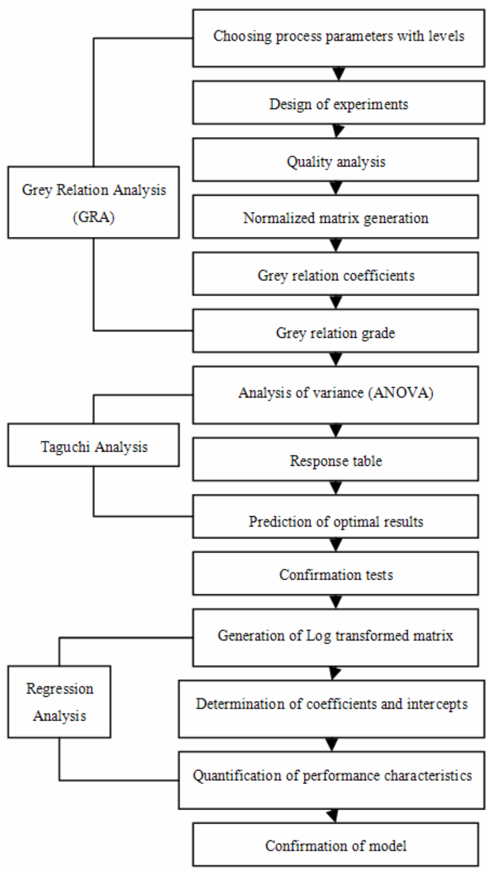

Fig. 1. Flow chart for analyzing performance characteristics.

(DOE) technique with a specialized single-ball controlled shot peening machine. Taguchi defines the quality of a product in terms of loss imported by the product to the society from the time product is shipped to the customer [12]. The Taguchi method [13, 14] is a systematic tool for designing and analyzing the experiments for improving product quality. However, with the Taguchi method only a single performance characteristic is optimized. Phadke et al. [15] suggested that the optimization of multi-performance characteristics became difficult by the Taguchi method. Deng [16, 17] proposed that GRA is a part of grey system theory for the optimization of multi-performance characteristics. Jeyapaul et al. [18] suggested several modifications to the original Taguchi method for multi-performance characteristic's optimization such as principal component analysis (PCA), data envelopment analysis (DEA) and GRA. In recent years, GRA has become a powerful tool to analyze the processes with multiple performance characteristics. Chen et al. [19] and Bin et al. [20] used GRA in different applications. Lin and Lin [21] discussed the combined orthogonal array and GRA to optimize the electrical discharge machining process with multi responses. Hence, in view of all, it is necessary to perform a comprehensive investigation using GRA to optimize the effect of shot peening parameters on tensile strength, surface hardness and surface roughness of the welded AISI 304 austenitic stainless steel.

Table 1. Chemical composition (wt %) of AISI 304 austenitic stainless steel.

Steel	C	Si	Mn	P	S	Ni	Cr
AISI 304	0.08	0.75	3.0	0.042	0.03	10	18

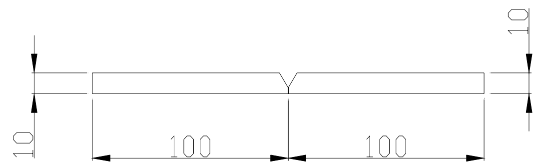

Fig. 2. Edge preparation (all dimensions in mm).

This paper proposes a novel design method based on GRA and Taguchi analysis to optimize the performance characteristics of welded AISI 304 austenitic stainless steel by shot peening. The optimization of process parameters such as pressure, shot size, exposure time and nozzle distance for tensile strength, surface hardness and surface roughness was investigated by using the approach. Further mathematical models were developed from the experimental results which are used in the quantification of tensile strength, surface hardness and surface roughness. The flow chart for analyzing performance characteristics is shown in Fig. 1. Thus, the results can be used by the engineers who are willing to search for an optimal solution of shot peening process of welded AISI 304 austenitic stainless steel.

2. Experimental setup

AISI 304 austenitic stainless steel was used for various tests. The composition of the material is shown in Table 1. For testing tensile strength, surface hardness and surface roughness, a flat plate having thickness of 10 mm was used. The plate was divided into two parts with the help of Power Hacksaw Machine. After that, these two pieces were welded together as shown in Fig. 2.

Edge preparation was done before welding as per standards. Single V joint was prepared because it was used for the sheet of thickness 8 ~ 16mm for arc and gas welding. GMAW was used to join these pieces. Elektriska Svetsnings - Aktiebolaget India (ESAB India) company's electrodes E-308-16 were used for welding. The welding current of 150amp with welding speed 350mm/min was set.

The specimens were prepared for tests (i.e. tensile, surface hardness & surface roughness test) after welding and cleaning as per ASTM standard. The welded plates were cut in different pieces with the help of the Power Hacksaw Machine for various specimens. The first part and the last part were scraped due to defects in the initiation and stoppage of welding.

The specimen for tensile strength test is shown in Fig. 3. These specimens were required to perform the tensile test at different process parameter levels. The shape and size of

Table 2. Process parameter and their levels.

Process parameter	Parameter designation	Levels L1	L2	L3
Pressure (Kg/cm^2)	P	2	4	6
Shot size (mm)	S	0.85	1.00	1.85
Exposure time (sec)	T	80	120	160
Nozzle distance (mm)	D	100	120	140

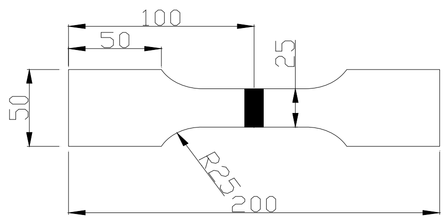

Fig. 3. Specimen for tensile test (all dimensions in mm).

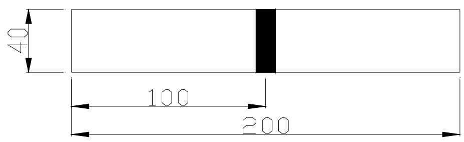

Fig. 4. Specimen for surface hardness and surface roughness test.

specimen for surface hardness and surface roughness was given in Fig. 4. Tensile strength of the specimens was determined by using a universal testing machine.

Vicker hardness test was used for measuring the surface hardness. The average surface roughness (R_a) was measured by using the Mitutoyo Surftest SJ-301 instrument. The sampling length of each measurement was set to 5mm.

2.1 Selection of shot peening parameters

In the shot peening process the shot size and incidence angle are the only two parameters which are controlled directly before the shot peening process starts and the remaining parameters, i.e., intensity, saturation, coverage etc., are evaluated after the peening process is complete. The desired magnitude of intensity, saturation, velocity and coverage is controlled by the air pressure, shot mass flow rate, nozzle type, feed rate of the nozzle along the work piece, nozzle distance from the work piece, and the work piece table speed. Therefore, in the present investigation the pressure (P), shot size (S), exposure time (T) and nozzle distance (D) are the controllable influential process parameters under consideration. These shot peening parameters along with their levels are shown in Table 2.

2.2 Design of experiments (DOE)

An orthogonal array is a full or fractional factorial matrix that ensures a balanced comparison of levels of any process.

Table 3. Experimental layout using L27 orthogonal array.

Run No.	P	S	T	D
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	2	2	2
5	1	2	2	2
6	1	2	2	2
7	1	3	3	3
8	1	3	3	3
9	1	3	3	3
10	2	1	2	3
11	2	1	2	3
12	2	1	2	3
13	2	2	3	1
14	2	2	3	1
15	2	2	3	1
16	2	3	1	2
17	2	3	1	2
18	2	3	1	2
19	3	1	3	2
20	3	1	3	2
21	3	1	3	2
22	3	2	1	3
23	3	2	1	3
24	3	2	1	3
25	3	3	2	1
26	3	3	2	1
27	3	3	2	1

Table 4. Experimental results for different shot peening parameters.

Run No.	Tensile strength (Mpa)	Surface hardness (VHN)	Surface roughness Ra (μm)
1	637.9	242	3.05
2	649.7	236	3.11
3	641.3	233	3.15
4	631.8	260	3.54
5	642.2	256	3.61
6	644.6	263	3.48
7	625.2	269	4.21
8	621.8	276	4.18
9	618.5	280	4.26
10	584.4	265	4.39
11	572.1	268	4.31
12	582.6	260	4.29
13	652.9	304	5.46
14	663.7	290	5.38
15	648.5	286	5.28
16	554.2	234	4.11
17	560.8	241	4.01
18	565.6	230	4.19
19	602.6	284	5.61
20	608.1	298	5.72
21	598.3	295	5.68
22	534.5	244	4.22
23	524.8	234	4.17
24	529.3	238	4.12
25	603.2	267	5.93
26	593.4	278	5.86
27	590.8	266	6.04

In the present analysis an L27 orthogonal array was used. There were three levels for each four factors and 27 runs. Table 3 shows the experimental layout for different process parameters at their respective level. The experimental results of tensile strength, surface hardness and surface roughness are depicted in Table 4 for these 27 runs.

3. Grey relational analysis (GRA)

It is an effective technique that can be used for decision making of multiple attributes. In GRA, the experimental results of tensile strength, surface hardness and surface roughness are normalized in the range between zero to one. The data for tensile strength and surface hardness is expressed as:

$$x'_i(j) = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}}. \quad (1)$$

And for surface roughness it is expressed as:

$$x'_i(j) = \frac{\max_j y_{ij} - y_{ij}}{\max_j y_{ij} - \min_j y_{ij}}. \quad (2)$$

Now a normalized matrix is generated with Eqs. (1) and (2). From the normalized matrix a reference value is determined as the largest value of normalized value for each criterion.

$$x'_0(j) = \max_{i=1}^{n} x'_i(j) \quad (3)$$

The next step is to construct the difference matrix by taking the difference between the normalized entity and reference value.

$$\Delta_{oi}(j) = | x'_o(j) - x'_i(j) | \quad (4)$$

Afterwards, the grey relational coefficients are determined by using Eq. (5). It represents the relationship between the desired and actual experimental results.

$$\delta_{oi}(j) = \frac{\min_{i=1}^{n} \min_{j=1}^{m} \Delta_{oi}(j) + \zeta \times \max_{i=1}^{n} \max_{j=1}^{m} \Delta_{oi}(j)}{\Delta_{oi}(j) + \zeta \times \max_{i=1}^{n} \max_{j=1}^{m} \Delta_{oi}(j)} \quad (5)$$

where ζ ($0 \le \zeta \le 1$) is known as the distinguishing coefficient or the index for distinguishability. If the value of ζ is small there will be higher distinguishability. In most situations, ζ takes the value of 0.5 because this value usually provides moderate distinguishing effects and good stability [22].

Then in the next stage a weighting method is used to compute the grey relational grade for each experiment. This grey relational grade is a single numerical value which depicts the optimization of multiple performance characteristics.

$$\gamma_{oi} = \frac{1}{m} \sum_{i=1}^{m} \delta_{oi}(j) \quad (6)$$

Table 5. Normalized matrix elements with reference sequence.

Run No.	Tensile strength (Mpa)	Surface hardness (VHN)	Surface roughness Ra (μm)
1	0.8143	0.1622	1.0000
2	0.8992	0.0811	0.9799
3	0.8387	0.0405	0.9666
4	0.7703	0.4054	0.8361
5	0.8452	0.3514	0.8127
6	0.8625	0.4460	0.8562
7	0.7228	0.5270	0.6120
8	0.6983	0.6216	0.6221
9	0.6746	0.6757	0.5953
10	0.4291	0.4730	0.5518
11	0.3405	0.5135	0.5786
12	0.4161	0.4054	0.5853
13	0.9222	1.0000	0.1940
14	1.0000	0.8108	0.2207
15	0.8906	0.7568	0.2542
16	0.2117	0.0541	0.6455
17	0.2592	0.1486	0.6789
18	0.2937	0.0000	0.6187
19	0.5601	0.7297	0.1438
20	0.5997	0.9189	0.1070
21	0.5292	0.8784	0.1204
22	0.0697	0.1892	0.6087
23	0.0000	0.0541	0.6254
24	0.0322	0.1081	0.6421
25	0.5644	0.5000	0.0368
26	0.4939	0.6486	0.0602
27	0.4752	0.4865	0.0000

The grey relational grade is calculated by using Eq. (6) while considering the same weightage for performance characteristics. i.e. 1. In Eq. (6) m represents the number of performance characteristics. Further, ANOVA and Taguchi analysis are performed on grey relational grade by using statistical software MINITAB 14 to determine the significant process parameter. Hence, it helps in predicting the best combination of process parameters for optimal performance characteristics.

4. Results and discussion

A normalized matrix was constructed for tensile strength and surface hardness by Eq. (1) and surface roughness by using Eq. (2). The elements of the normalized matrix along with the reference sequence element are shown in Table 5.

At the next step, the grey relational coefficients were determined by using Eq. (5). It expresses the relationship between the best (reference value) and actual normalized value. The grey relational coefficients are represented in Table 6.

Table 6. Grey relational coefficients for performance characteristics.

Run No.	Tensile strength (Mpa)	Surface hardness (VHN)	Surface roughness Ra (μm)
1	0.7291	0.3737	1.0000
2	0.8322	0.3524	0.9614
3	0.7561	0.3426	0.9373
4	0.6852	0.4568	0.7531
5	0.7636	0.4353	0.7275
6	0.7843	0.4744	0.7766
7	0.6434	0.5139	0.5631
8	0.6237	0.5692	0.5695
9	0.6058	0.6066	0.5527
10	0.4669	0.4868	0.5273
11	0.4312	0.5068	0.5426
12	0.4613	0.4568	0.5466
13	0.8654	1.0000	0.3828
14	1.0000	0.7255	0.3908
15	0.8204	0.6727	0.4013
16	0.3881	0.3458	0.5851
17	0.4030	0.3700	0.6090
18	0.4145	0.3333	0.5674
19	0.5320	0.6491	0.3687
20	0.5554	0.8605	0.3589
21	0.5150	0.8043	0.3624
22	0.3496	0.3814	0.5610
23	0.3333	0.3458	0.5717
24	0.3406	0.3592	0.5828
25	0.5344	0.5000	0.3417
26	0.4970	0.5873	0.3473
27	0.4879	0.4933	0.3333

Table 7. Grey relational grade for performance characteristics.

Run No.	Grey relational grade
1	0.701
2	0.7153
3	0.6787
4	0.6317
5	0.6421
6	0.6784
7	0.5734
8	0.5875
9	0.5883
10	0.4937
11	0.4936
12	0.4882
13	0.7494
14	0.7054
15	0.6315
16	0.4397
17	0.4606
18	0.4384
19	0.5166
20	0.5916
21	0.5606
22	0.4307
23	0.4169
24	0.4276
25	0.4587
26	0.4772
27	0.4382

Table 8. Response table for grey relational grade.

Level	P	S	T	D
1	0.6440	0.5821	0.5232	0.6173
2	0.5445	0.5904	0.5335	0.5511
3	0.4798	0.4958	0.6116	0.5000
Delta	0.1643	0.0946	0.0884	0.1173
Rank	1	3	4	2

Using Eq. (6) the grey relational grade of comparability sequence for j = 1-27 was obtained and shown in Table 7. The weighting value of different performance characteristics would be decided by the manufacturer. In the present analysis the same values are assigned to the performance characteristics by assuming that they are equally important. Hence, for optimization the multiple performance characteristics can be converted into a single grey relational grade. The greatest value of grey relational grade represents the level of process parameters for optimal performance characteristics.

ANOVA and the response table values are computed for determining the significant factors, their desirability and the confidence. A response table (Table 8) is made for different process parameters. Pressure has greatest impact on the performance characteristics, whereas the exposure time has the least impact. It is also known that for a process parameter whose p-value is less than 0.05 has a significant effect on the performance characteristics, and p-value between 0.05 and 0.1 shows the low significant effect. The parameter has the least effect on the process whose p-value is more than 0.1. Hence, it is found that all the process parameters have significant effect on the performance characteristics (Table 9) of welded AISI 304 austenitic stainless steel.

5. Confirmation test

The best combination of process parameters for optimum performance characteristics is determined by Taguchi analysis (Table 8) as P1 S2 T3 D1. Further the investigation is confirmed by ANOVA (Table 9). The optimal grey relational grade (γ_{opt}) is predicted by using the following equation:

Table 9. The ANOVA for grey relational grade.

Source	df	Sum of squares	Mean square	F	p-value
P	2	0.12323	0.06162	84.28	0.000
S	2	0.04945	0.02473	33.82	0.000
T	2	0.04203	0.02102	28.75	0.000
D	2	0.06224	0.03112	42.56	0.000
Error	18	0.01316	0.00073		
Total	26	0.2901			
S = 0.0270384 R-Sq = 95.46% R-Sq(adj) = 93.45%					

Table 10. Experimental and predicted values of grey relational grade.

Performance characteristics	Predicted value	Experimental value	Regression analysis
Optimal parameters	P1S2T3D1	P1S2T3D1	P1S2T3D1
Tensile strength (MPa)		671.3	675.5
Surface hardness (VHN)		267	263
Surface roughness (μm)		3.81	3.76
Grey relational grade	0.7950	0.7619	0.7788

$$\gamma_{opt} = \gamma_m + \sum_{i=1}^{n} (\gamma_i - \gamma_m) \quad (7)$$

where γ_m is the average of grey relational grade, γ_i is the average of grey relational grade at optimum level and n is the number of significantly affecting process parameters. Pressure, shot size, exposure time and nozzle distance are all the significant parameters used for predicting the optimal grey relational grade. The predicted value of optimal grey relational grade is expressed as:

$$\gamma_{opt} = \gamma_m + \sum_{i=1}^{4} (\gamma_i - \gamma_m)$$
$$= 0.5561 + (0.6440 - 0.5561) + (0.6173 - 0.5561) + (0.5904 - 0.5561) + (0.6116 - 0.5561) = \mathbf{0.7950}.$$

Finally, three experiments are conducted by using best process parameters for optimum performance characteristics, and the mean results are presented in Table 10. Hence, using the present approach, shot peening of welded AISI 304 austenitic stainless steel is successfully optimized for the tensile strength, surface hardness and surface roughness.

6. Regression analysis of performance characteristics

Regression analysis for the tensile strength (TS), surface hardness (VHN) and surface roughness (SR) of the materials was obtained by using statistical software MINITAB 14. The correlations were formed for process parameters by assuming

Table 11. Log transformed for process parameters.

P	ln (P)	S	ln (S)	T	ln (T)	D	ln (D)
2	0.6931	0.85	-0.1625	80	4.382	100	4.6052
2	0.6931	0.85	-0.1625	80	4.382	100	4.6052
2	0.6931	0.85	-0.1625	80	4.382	100	4.6052
2	0.6931	1	0.0000	120	4.7875	120	4.7875
2	0.6931	1	0.0000	120	4.7875	120	4.7875
2	0.6931	1	0.0000	120	4.7875	120	4.7875
2	0.6931	1.85	0.6152	160	5.0752	140	4.9416
2	0.6931	1.85	0.6152	160	5.0752	140	4.9416
2	0.6931	1.85	0.6152	160	5.0752	140	4.9416
4	1.3863	0.85	-0.1625	120	4.7875	140	4.9416
4	1.3863	0.85	-0.1625	120	4.7875	140	4.9416
4	1.3863	0.85	-0.1625	120	4.7875	140	4.9416
4	1.3863	1	0.0000	160	5.0752	100	4.6052
4	1.3863	1	0.0000	160	5.0752	100	4.6052
4	1.3863	1	0.0000	160	5.0752	100	4.6052
4	1.3863	1.85	0.6152	80	4.382	120	4.7875
4	1.3863	1.85	0.6152	80	4.382	120	4.7875
4	1.3863	1.85	0.6152	80	4.382	120	4.7875
6	1.7918	0.85	-0.1625	160	5.0752	120	4.7875
6	1.7918	0.85	-0.1625	160	5.0752	120	4.7875
6	1.7918	0.85	-0.1625	160	5.0752	120	4.7875
6	1.7918	1	0.0000	80	4.382	140	4.9416
6	1.7918	1	0.0000	80	4.382	140	4.9416
6	1.7918	1	0.0000	80	4.382	140	4.9416
6	1.7918	1.85	0.6152	120	4.7875	100	4.6052
6	1.7918	1.85	0.6152	120	4.7875	100	4.6052
6	1.7918	1.85	0.6152	120	4.7875	100	4.6052

Table 12. Log transformed for performance characteristics.

TS	ln (TS)	VHN	ln (VHN)	SR	ln (SR)
637.9	6.4582	242	5.4889	3.05	1.1151
649.7	6.4765	236	5.4638	3.11	1.1346
641.3	6.4635	233	5.4510	3.15	1.1474
631.8	6.4486	260	5.5607	3.54	1.2641
642.2	6.4649	256	5.5452	3.61	1.2837
644.6	6.4686	263	5.5722	3.48	1.2470
625.2	6.4381	269	5.5947	4.21	1.4375
621.8	6.4326	276	5.6204	4.18	1.4303
618.5	6.4273	280	5.6348	4.26	1.4493
584.4	6.3706	265	5.5797	4.39	1.4793
572.1	6.3493	268	5.5910	4.31	1.4609
582.6	6.3675	260	5.5607	4.29	1.4563
652.9	6.4814	304	5.7170	5.46	1.6974
663.7	6.4978	290	5.6699	5.38	1.6827
648.5	6.4747	286	5.6560	5.28	1.6639
554.2	6.3175	234	5.4553	4.11	1.4134
560.8	6.3294	241	5.4848	4.01	1.3888
565.6	6.3379	230	5.4381	4.19	1.4327
602.6	6.4013	284	5.6490	5.61	1.7246
608.1	6.4103	298	5.6971	5.72	1.7440
598.3	6.3941	295	5.6870	5.68	1.7370
534.5	6.2813	244	5.4972	4.22	1.4398
524.8	6.263	234	5.4553	4.17	1.4279
529.3	6.2715	238	5.4723	4.12	1.4159
603.2	6.4022	267	5.5872	5.93	1.7800
593.4	6.3859	278	5.6276	5.86	1.7681
590.8	6.3815	266	5.5835	6.04	1.7984

Table 13. Coefficients and intercepts for tensile strength.

Predictor	Coef	SE Coef	T	p-value
Constant	7.23877	0.06677	108.41	0.000
ln(P)	-0.08960	0.003806	-23.54	0.000
ln(S)	-0.03465	0.005154	-6.72	0.000
ln(T)	0.121562	0.006071	20.02	0.000
ln(D)	-0.27109	0.01256	-21.59	0.000
S = 0.00897097 R-Sq = 98.5% R-Sq(adj) = 98.3%				

Table 14. Coefficients and intercepts for surface hardness.

Predictor	Coef	SE Coef	T	p-value
Constant	4.5997	0.1506	30.54	0.000
ln(P)	0.033097	0.008586	3.85	0.001
ln(S)	-0.02062	0.01163	-1.77	0.090
ln(T)	0.27548	0.01370	20.11	0.000
ln(D)	-0.07935	0.02833	-2.8	0.010
S = 0.0202376 R-Sq = 95.1% R-Sq(adj) = 94.3%				

a log transformed response variable and are in Tables 11 and 12. The following model was assumed for best curve fitting:

$$\ln(Y) = \beta_0 + \beta_1 \ln(P) + \beta_2 \ln(S) + \beta_3 \ln(T) + \beta_4 \ln(D)$$

where Y is the performance characteristic and β_0, β_1, β_2, β_3, β_4 are the regression coefficients.

6.1 Quantification of tensile strength

The regression analysis results for tensile strength are represented in Table 13. It yields the following correlation between the tensile strength and the process parameters:

$$\ln(TS) = 7.24 - 0.0896 \ln(P) - 0.0347 \ln(S) + 0.122 \ln(T) - 0.271 \ln (D). \quad (8)$$

The above equation can also be expressed in exponential form as follows:

$$(TS)_1=1394.1(P)^{-0.0896} (S)^{-0.0347} (T)^{0.122} (D)^{-0.271} . \quad (9)$$

6.2 Quantification of surface hardness

Similarly, the regression analysis results for surface hardness are tabulated in Table 14. This yields the following correlation between the surface hardness and the process parameters:

$$\ln(VHN) = 4.60 + 0.0331 \ln(P) - 0.0206 \ln(S) + 0.275 \ln(T) - 0.0794 \ln(D). \quad (10)$$

The above equation can also be expressed in exponential form as follows:

Table 15. Coefficients and intercepts for surface roughness.

Predictor	Coef	SE Coef	T	p-value
Constant	0.2612	0.1258	2.08	0.050
ln(P)	0.337625	0.007168	47.1	0.000
ln(S)	0.131708	0.009708	13.57	0.000
ln(T)	0.42622	0.01143	37.27	0.000
ln(D)	-0.26335	0.02365	-11.14	0.000
S = 0.0168957 R-Sq = 99.4% R-Sq(adj) = 99.3%				

Table 16. ANOVA for tensile strength.

Source	DF	SS	MS	F	p-value
Regression	4	0.118008	0.02950	366.58	0.000
Residual error	22	0.001771	0.00008		
Total	26	0.119779			
S = 0.00897097 R-Sq = 98.5% R-Sq(adj) = 98.3%					

Table 17. ANOVA for surface hardness.

Source	DF	SS	MS	F	p-value
Regression	4	0.176272	0.044068	107.60	0.000
Residual error	22	0.00901	0.00041		
Total	26	0.185282			
S = 0.0202376 R-Sq = 95.1% R-Sq(adj) = 94.3%					

$$(VHN)_1 = 99.5(P)^{0.0331} (S)^{-0.0206} (T)^{0.275} \ln(D)^{-0.0794}. \quad (11)$$

6.3 Quantification of surface roughness

Similarly, the results of regression analysis for surface roughness are in Table 15. It gives the following correlation between the surface roughness and the process parameters:

$$\ln(SR) = 0.261 + 0.338 \ln(P) + 0.132 \ln(S) + 0.426 \ln(T) – 0.263 \ln(D). \quad (12)$$

The above equation can also be expressed in exponential form as follows:

$$(SR)_1 = 1.3 (P)^{0.338} (S)^{0.132} (T)^{0.426} (D)^{-0.263}. \quad (13)$$

The regression analysis Eqs. (9), (11) and (13) determine the value of the tensile strength, surface hardness and surface roughness, respectively, for the welded AISI 304 austenitic stainless steel. This would serve as a useful guide for selecting proper values of process parameters to obtain desired tensile strength, surface hardness and surface roughness of the welded component.

It can be seen from Tables 16, 17 and 18 that p-values for the response tensile strength, surface hardness and surface roughness are less than 0.05, which shows that they are sig-

Table 18. ANOVA for surface roughness.

Source	DF	SS	MS	F	p-value
Regression	4	1.1178	0.27945	978.93	0.000
Residual error	22	0.00628	0.00029		
Total	26	1.12408			
S = 0.0168957 R-Sq = 99.4% R-Sq(adj) = 99.3%					

nificant. Also, the values of R-sq (adj) are more than 90%, which indicates a good fit. It confirms that the model adequately describes the observed data.

7. Conclusions

This study incorporates GRA based on Taguchi orthogonal array. It provides a parameter design method, to enhance effectively the performance of the shot peening process on welded AISI 304 austenitic stainless steel. Using this analysis the multiple-performance characteristics of the component, i.e., tensile strength, surface hardness and surface roughness, can be converted into optimization of a single performance characteristic called the grey relational grade. As a result, optimization of complicated multiple-performance characteristics can be greatly simplified through this approach. Also, through the response analysis and ANOVA, we can obtain the optimal parameters and major factors that affect the performance characteristics. The analytical results are summarized as follows:

Tables 8 and 9 show that pressure, shot size, exposure time and nozzle distance are the process parameters which significantly affect the performance characteristics. The significant parameters affecting the performance characteristics are at 95% confidence level. The order of the importance for the controllable factors to the grey relational grade, in sequence, is the pressure, nozzle distance, shot size and exposure time.

The grey relational grade is best for shot peened welded AISI 304 austenitic stainless steel at level 1 for pressure ($2kg/cm^2$), level 2 for shot size (1 mm), level 3 for exposure time (160sec) and level 1 for nozzle distance (100 mm). At these process parameters the experimental values of tensile strength, surface hardness and surface roughness are 671.3MPa, 267VHN and 3.81μm, respectively. The calculated grey relational grade for these optimal values of performance characteristics is 0.7619, which is higher from the grey relational grade (0.7494) among the 27 experiments.

Regression models correlating tensile strength, surface hardness and surface roughness with process parameters have also been obtained. These equations provide a useful guide for setting proper values of process parameters so as to obtain desired tensile strength, surface hardness and surface roughness of the shot peened welded AISI 304 austenitic stainless steel component. The grey relational grade is determined by using the regression analysis models at optimum level of process parameters as 0.7788, which is near to 0.7619.

Nomenclature

R-sq : Coefficient of determination
R-sq (adj) : Adjusted multiple coefficient of determination
$x'_i(j)$: Element of normalized matrix
$x'_o(j)$: Reference value from normalized matrix
$\delta_{oi}(j)$: Grey relational coefficient
$\gamma_{oi}(j)$: Grey relational grade
DOE : Design of experiment
γ_{opt} : Optimal grey relational grade
γ_m : Average grey relational grade
γ_i : Average of grey relational grade at optimum level

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