Optimization of multi performance characteristics of shot peened welded AISI 304 austenitic stainless steel: a grey relational approach with Taguchi analysis

Dr. Lakhwinder Singh
Associate Professor,
Department of Mechanical Engineering, YMCA University of Science & Technology,
Faridabad -121006,
Haryana , India.

Dr. R.A. Khan
Retd. Professor,
Department of Mechanical Engineering,
Jamia Millia Islamia,
New Delhi,
India-110025

Dr. M.L. Aggarwal
Professor,
Department of Mechanical Engineering,
YMCA University of Science & Technology,
Faridabad-121006,
Haryana, India

Abstract

Shot peening is one of the cold working process that changes the mechanical and surface properties of the material such as tensile strength, surface roughness, surface hardness, impact strength etc. by inducing compressive residual stress field in thin skin layer called deformed layer. AISI 304 austenitic stainless steel usually forms irregular weld beads during butt welding. Initiation of cracks is dependent on surface and near-surface conditions, so that local stress field caused by surface hardness and other surface characteristics is important. In the present analysis the Grey relational analysis (GRA) with principal component analysis (PCA) and Taguchi analysis is used to optimization the multi performance characteristics of welded AISI 304 austenitic stainless steel Optimal conditions for critical parameters such as pressure, shot size, exposure time, nozzle distance and nozzle angle affecting surface hardness and impact strength are observed. Analysis of variance (ANOVA) is performed and signal-to-noise (S/N) ratio is determined to know the level of importance of parameters. The complete analysis will be helpful to the manufacturer in deciding the shot peening parameters for best combination of performance characteristics of welded joint.

1. Introduction

Shot peening is used now a days in hundreds of different components of automobiles, aircraft and marine industries like railway and automobile leaf spring, helical spring, gears, axle bearing, crankshafts, milling cutters, connecting rod, cylinder block, valve springs, washers etc. [1, 2]. The major applications are related to improvement and restoration of mechanical properties and reliability of machine elements by increasing their surface hardness, tensile strength, surface finish, impact strength, fatigue strength etc. [3, 4]. It is applicable to ferrous and non-ferrous parts but is mostly used on steel surfaces. The steel balls, or shots, are thrown against the surface either by compressed air or by centrifugal force of rotating wheel. The intensity of the process can be varied by regulating the size of shot, the hardness of shot, and the speed at which it is fired, the length of time, the distance of nozzle from the surface and the work exposed to the shot. The result of the interaction of material surface with the shot peening parameters is generation of residual stresses, strain hardening of the surface and sub surface layers, changes in microstructure and substructure of material, changes in surface conditions and hardening characteristics of the material.

Austenitic stainless steel can be welded by most of the common arc welding processes. The commonly used processes are flux cored arc welding, gas metal-arc welding, gas tungsten-arc welding, shielded metal-arc welding with coated electrodes and submerged arc welding. Shamsul and Hisyam discussed the method of spot welding of austenitic stainless steel type 304 [5]. The cost of stainless steel is approximately six times more than that of mild steel. For this reason, 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. The low amperage is required to weld austenitic stainless steel than carbon steel because of its low melting point, high electric resistance and low thermal conductivity [6].

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

Austenitic stainless steel	**C**	**Si**	**Mn**	**P**	**S**	**Ni**	**Cr**	**Mo**	**V**
AISI 304	0.08	0.57	1.6	0.021	0.02	9.83	18.78	0.25	0.07

Type 308 electrodes were used to weld AISI 304 austenitic stainless steel [7, 8]. Ojha et. al. [9] investigated the optimization of shot peening parameters to improve fatigue strength of welded steel. Liu et. al. [10] has presented in their work the microstructure and mechanical properties of welded austenitic stainless steel. It was also noticed by Li et. al. [11] that residual stress was induced in weld by shot peening.

Only a few authors have used the design of experiment (DoE) technique with a specialized single-ball controlled shot peening machine. The Taguchi method [12, 13] is a systematic tool for designing and analyzing the experiments for improving product quality. However, it is found that with Taguchi Method only a single performance characteristic is optimized. Phadke et. al. [14] suggested that the optimization of multi performance characteristics became difficult by Taguchi method. Deng [15, 16] proposed that grey relational analysis (GRA) is a part of grey system theory for the optimization of multi performance characteristics. Jeyapaul et. al. 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 [17]. In recent years, GRA has become a powerful tool to analyze the processes with multiple performance characteristics. Chen et. al. [18], Bin et. al. [19] and Hsiao et. Al. [20] are making use of GRA in different applications. Author discussed the combined orthogonal array and GRA to optimize the electrical discharge machining process with multi response [21].

Hence in view of all, it is necessary to carry out comprehensive investigations using GRA with PCA and Taguchi analysis to evaluate the effect of shot peening parameters such as pressure, shot size, exposure time, nozzle distance and nozzle angle on surface integrity aspects as surface hardness and impact strength of the material. ANOVA and response tables were used carried out to identify the significant peening parameters. It is believed that this investigation helps the industries for reduction of performance variation and to increase productivity.

2. Experimental set up

The material AISI 304 austenitic stainless steel is used for various surface hardness and impact test. The composition of the material is shown in Table 1. A flat plate having thickness of 10 mm was used for making the specimens. The mechanical properties of the material were: tensile strength 617MPa, fatigue strength 228MPa and surface hardness 271VHN.

A 10mm thick plate of AISI 304 austenitic stainless steel was divided into two parts with the help of power hacksaw machine.

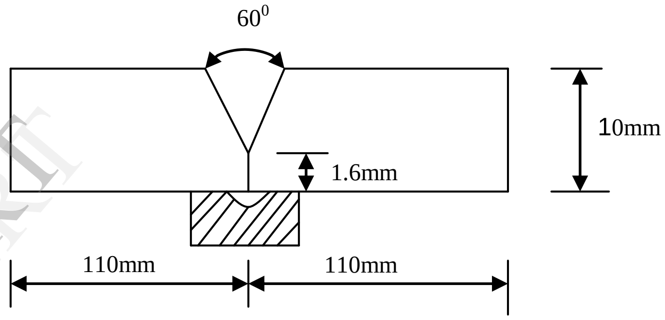

Figure 1: Edge preparation (all dimensions in mm).

Edge preparation was done before welding as per standards as shown in Figure 1. Single V joint was prepared because it was used for the sheet of thickness 8 ~ 16mm for arc and gas welding. GMAW with spray arc transfer was used to join these pieces. ESAB India company's electrodes E308-16 were used for welding. The welding parameters were set as follows:

- Electrode size : 1.6 mm
- Pass : 2
- Current DC (+) : 300 amp
- Arc voltage : 25V
- Wire feed rate : 85 mm/sec
- Arc speed : 6.5 mm/sec
- Electrode required : 0.405 kg/m
- Shielding gas : 98% Argon +2% oxygen
- Gas flow rate: 16.5 l/min

Figure 2: Plates after welding.

After welding the plates are shown in Figure 2. The specimens were prepared for tests (i.e. surface hardness & impact test) after welding and cleaning as per standard. The welded plates were cut into different pieces with the help of power hacksaw machine to obtain various specimens. The first part and the last part were scraped due to defects in the initiation and stoppage of welding.

The shape and size of work piece for surface hardness is given in Figure 3. Vicker hardness test was used for measuring the surface hardness. The charpy impact test was done on welded specimens to measure the impact strength. The V-notch was prepared as per standard. The specimen size 10 mm X 10 mm X 55 mm with a V-notch 2 mm deep, 45^0 angle and 0.25 mm notch root radius was taken. WOLPERT impact testing machine pendulum type PW 30/15 was used for experimentation.

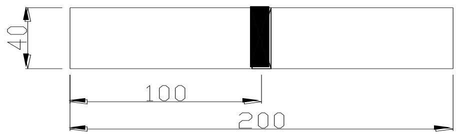

Figure 3: Specimen for surface hardness test.

In shot peening process the parameters are divided into two categories one is controlled before the start of the process i.e. shot size & nozzle angle and the remaining are evaluated after shot peening process i.e. intensity, saturation, coverage etc. The desired magnitude of intensity, saturation, velocity and coverage are 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 pressure, shot size, exposure time, nozzle distance and nozzle angle are the controllable influential process parameters under consideration. These shot peening parameters along with their levels are shown in Table 2.

3. Experimental Design

The experimental design was based on full factorial design considering five factors each at three levels. An orthogonal array is a fractional factorial matrix that ensures a balanced comparison of levels of any parameter. In the present analysis a L27 orthogonal array is used. For three levels of each five factors there are 27 runs. The experimental results for surface hardness (VHN) and impact strength (IS) are depicted in Table 3 for different 27 runs.

Table 2: Shot peening parameter and their levels for welded AISI 304 austenitic stainless steel.

Process Parameter	**Parameter Designation**	**Levels**		
		L1	L2	L3
Pressure (MPa)	P	0.196	0.392	0.588
Shot Size (mm)	S	0.85	1.00	1.85
Exposure Time (Sec)	T	80	120	160
Nozzle Distance (mm)	D	100	120	140
Nozzle Angle θ	E	60^0	75^0	90^0

4. Signal-to-noise (S/N) ratio

Taguchi method is used to determine signal-to-noise (S/N) ratio. It is used to represent a performance characteristic and the largest value of S/N ratio is always desired. In this method, there are three types of S/N ratios i.e. the lower-the-better, the higher-the-better, and the nominal-the-better.

In the present analysis S/N ratio with a higher-the-better characteristic is used, that can be expressed as:

$$(S/N)_{HB}=-10\text{Log}\left[\frac{1}{r}\sum_{i=1}^{r}\frac{1}{y_i^2}\right] \qquad (1)$$

where:

y_i = value of the performance characteristic in observation i

r = number of repetitions in a trial

The results of S/N ratios for different performance characteristics are shown in Table 4.

5. Grey relational analysis (GRA) with Principal component analysis (PCA)

5.1 Grey relational coefficients

The GRA is employed to analyze the complicated inter-relationships between the S/N ratios of performance characteristics. A linear normalization of the S/N ratio is performed in the range between zero and unity. The normalized S/N ratio y_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed by Eq. (2). The normalized matrix is represented in Table 5.

Larger-the-better

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

Table 3: Experimental layout using L27 orthogonal array.

Exp. No.	P	S	T	D	E	VHN	IS
1	1	1	1	1	1	274	221.61
2	1	1	1	1	2	286	229.29
3	1	1	1	1	3	301	240.19
4	1	2	2	2	1	302	236.59
5	1	2	2	2	2	312	242.28
6	1	2	2	2	3	320	255.64
7	1	3	3	3	1	312	234.19
8	1	3	3	3	2	320	241.01
9	1	3	3	3	3	328	245.84
10	2	1	2	3	1	329	218.43
11	2	1	2	3	2	322	223.39
12	2	1	2	3	3	335	234.11
13	2	2	3	1	1	366	237.72
14	2	2	3	1	2	372	248.23
15	2	2	3	1	3	380	246.45
16	2	3	1	2	1	334	212.33
17	2	3	1	2	2	347	224.92
18	2	3	1	2	3	332	216.21
19	3	1	3	2	1	380	221.51
20	3	1	3	2	2	398	233.95
21	3	1	3	2	3	395	239.55
22	3	2	1	3	1	344	212.43
23	3	2	1	3	2	340	224.88
24	3	2	1	3	3	358	229.28
25	3	3	2	1	1	366	215.92
26	3	3	2	1	2	381	230.89
27	3	3	2	1	3	392	239.35

Now from the normalized matrix a reference value is determined as the largest value of normalized value for each criterion.

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

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

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

Afterwards the grey relational coefficients are determined by using Eq. (5) and they are presented in Table 6. It represents the relationship between the desired and actual experimental results.

Table 4: S/N ratios for performance characteristics of welded AISI 304 austenitic stainless steel.

Exp. No.	S/N_{VHN}	S/N_{IS}
1	48.7550	46.9118
2	49.1273	47.2077
3	49.5713	47.6111
4	49.6001	47.4799
5	49.8831	47.6864
6	50.1030	48.1526
7	49.8831	47.3914
8	50.1030	47.6407
9	50.3175	47.8131
10	50.3439	46.7862
11	50.1571	46.9813
12	50.5009	47.3884
13	51.2696	47.5213
14	51.4109	47.8971
15	51.5957	47.8346
16	50.4749	46.5402
17	50.8066	47.0406
18	50.4228	46.6975
19	51.5957	46.9079
20	51.9977	47.3825
21	51.9319	47.5879
22	50.7312	46.5443
23	50.6296	47.0390
24	51.0777	47.2073
25	51.2696	46.6859
26	51.6185	47.2681
27	51.8657	47.5807

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

where ζ ($0 \le \zeta \le 1$) is the distinguishing coefficient or the index for distinguishability and ζ takes the value of 0.5 because this value usually provides moderate distinguishing effects and good stability.

5.2 Principal component analysis (PCA)

In the next stage a weightage method is used to analyze the weightage of each performance characteristic. The weightage assigned to the performance characteristics is either decided by the manufacturer or determined by PCA.

The elements of Table 6 represent the grey relational coefficients for the multi performance characteristics of shot peened welded AISI 304 austenitic stainless steel. This data is used to evaluate the correlation coefficient matrix and further used to evaluate the corresponding eigenvalues and eigenvectors from the following equation:

$$[(CC)_{jk} - \beta_l I_m]\, E_{il} = 0 \qquad (6)$$

Table 5: Normalized matrix elements.

Exp. No.	**VHN**	**IS**
1	0.0000	0.2305
2	0.1148	0.4140
3	0.2517	0.6642
4	0.2606	0.5828
5	0.3479	0.7109
6	0.4157	1.0000
7	0.3479	0.5279
8	0.4157	0.6825
9	0.4819	0.7894
10	0.4900	0.1526
11	0.4324	0.2736
12	0.5384	0.5260
13	0.7755	0.6085
14	0.8190	0.8415
15	0.8760	0.8028
16	0.5304	0.0000
17	0.6327	0.3103
18	0.5143	0.0976
19	0.8760	0.2280
20	1.0000	0.5224
21	0.9797	0.6498
22	0.6094	0.0025
23	0.5781	0.3094
24	0.7163	0.4137
25	0.7755	0.0904
26	0.8831	0.4514
27	0.9593	0.6453

where β_l represents the eigenvalues;

$\sum_{l=1}^{n} \beta_l = n$, l = 1, 2, 3,……..n; and

$E_{il} = [a_{li}\ a_{l2}\ a_{l3}\ ……..a_{ln}]^T$ is the eigenvector corresponding to the eigenvalue β_l.

The eigenvalues are shown in Table 7 and the eigenvector corresponding to each eigenvalue is listed in Table 8 respectively. The results are obtained by using statistical software MINITAB 14.

Hence, for this study, the square of corresponding eigenvectors is selected as the weighting values of the related performance characteristic, represented by ω_{VHN} and ω_{IS}. The weightage for parent and welded AISI 304 austenitic stainless steel is given in Table 9.

Table 6: Grey relational coefficients for performance characteristics.

Exp. No.	**δ_{oi} (VHN)**	**δ_{oi} (IS)**
1	0.3333	0.3938
2	0.3610	0.4604
3	0.4006	0.5982
4	0.4034	0.5451
5	0.4340	0.6336
6	0.4611	1.0000
7	0.4340	0.5144
8	0.4611	0.6116
9	0.4911	0.7037
10	0.4950	0.3711
11	0.4683	0.4077
12	0.5200	0.5134
13	0.6901	0.5608
14	0.7343	0.7593
15	0.8013	0.7171
16	0.5157	0.3333
17	0.5765	0.4203
18	0.5073	0.3565
19	0.8013	0.3931
20	1.0000	0.5115
21	0.9610	0.5881
22	0.5614	0.3339
23	0.5424	0.4199
24	0.6380	0.4603
25	0.6901	0.3547
26	0.8105	0.4768
27	0.9247	0.5850

Table 7: The eigenvalues and proportions for principal components.

Principal Component	**Eigenvalue**	**Proportion (%)**
First	1.0702	53.5
Second	0.9298	46.5

5.3 Grey relational grade

In the next step grey relational grades are calculated using on Eq. (7) from data listed in Table 6 in the form of grey relational coefficients. Thus, the optimization design is performed with respect to a single grey relational grade rather than complicated multi performance characteristics. The grey relational grade is determined from following equation:

$$\gamma_{oi} = \sum_{i=1}^{m} \delta_{oi}(j)\omega_i \qquad (7)$$

Table 8: The Eigenvectors for principal components.

Performance characteristics	First principal component	Second principal component
VHN	0.707	0.707
IS	0.707	- 0.707

Table 9: The weightage of each performance characteristic.

Performance	Weightage
ω_{VHN}	0.5
ω_{IS}	0.5

In this equation m is the number of performance characteristics and ω_i is the weightage assigned to the respective performance characteristic. The results of grey relational grade are represented in Table 10.

Table 10 shows the shot peening parameter's setting of experiment no. 21 has the highest value of grey relational grade (0.7745). Thus, the experiment no. 21 gives the best combination of process parameters among the twenty seven experiments welded AISI 304 austenitic stainless steel.

6. Analysis of results

Further Taguchi analysis and ANOVA are performed on grey relational grade by using statistical software MINITAB 14 to determine the significant process parameter. Hence they help in predicting the best combination of process parameters for optimal performance characteristics.

6.1 Taguchi analysis

Taguchi analysis is performed to generate the response table i.e. the average grey relational grade for each factor level, by using statistical software MINITAB 14. It helps to determine the influencing level of process parameter. The procedure was to group the grey relational grades firstly by factor level for each column in the orthogonal array, and then to average them.

The generated response table is shown in Table 11 for each factor level. The average grey relational grades represent the level of correlation between the reference and the comparability sequences. Larger value of average grey relational grade shows that the comparability sequence exhibits a stronger correlation with the reference sequence. On the bases of this statement this analysis helps to select the level of process parameters that provides the largest performance characteristics. In Table 11, P3, S2, T3, D1 and E3 have largest value of average grey relational grade for factors P, S, T, D and E respectively. Hence P3S2T3D1E3 is the best combination of shot peening parameters for optimal performance characteristics of welded AISI 304 austenitic stainless steel. It is restated that for welded AISI 304 austenitic stainless steel the best combination of shot peening parameters are as: pressure 0.588MPa, shot size 1mm, exposure time 160sec, nozzle distance 100mm and nozzle angle is 90^0. The impact of each shot peening parameter can be presented clearly by means of the grey relational grade graphs. These graphs shows the change in the response,

Table 10: Grey relational grade.

Exp. No.	Grey relational grade
1	0.3636
2	0.4107
3	0.4994
4	0.4743
5	0.5338
6	0.7306
7	0.4742
8	0.5364
9	0.5974
10	0.4331
11	0.4380
12	0.5167
13	0.6255
14	0.7468
15	0.7592
16	0.4245
17	0.4984
18	0.4319
19	0.5972
20	0.7557
21	0.7745
22	0.4477
23	0.4811
24	0.5491
25	0.5224
26	0.6436
27	0.7549

Table 11: Response table for the grey relational grade.

Level	P	S	T	D	E
1	0.5134	0.5321	0.4563	0.5918	0.4847
2	0.5416	0.5942	0.5608	0.5801	0.5605
3	0.6140	0.5426	0.6519	0.4971	0.6237
Delta	0.1006	0.0621	0.1956	0.0947	0.1390
Rank	3	5	1	4	2

when the parameters changes their level from 1 to level 3. The response graphs for shot peening parameters are presented in Fig. 4. In these figures, the higher value of response gives the high value of performance characteristics.

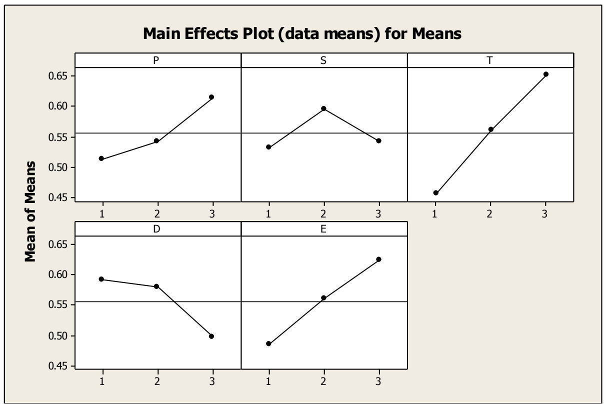

Fig. 4: Response graphs of shot peening parameters.

The order of importance of process parameters is also observed from Table 11 i.e. by calculating the difference between the maximum and minimum value of the average grey relational grade for each factor. The last row of response tables indicates that the exposure time has stronger effect on the multi-performance characteristics than other parameters.

6.2 ANOVA

The purpose of the ANOVA is to investigate which parameters of shot peening process affect significantly the performance characteristics. This is achieved by separating the total variability of the grey relational grades. To evaluate the impact of each process parameters on performance characteristics, the total sum of the squared deviations can be utilized. Table 12 gives the results of the ANOVA for performance characteristic using grey relational grade in Table 10.
According to Table 12, the exposure time with 41.86% of contribution, is the most significant controlled parameters of the shot peened welded AISI 304 austenitic stainless steel. It is also found that the p-value of all the factors is less than 0.05 that represents significant effect on the performance characteristics.

7. Confirming experimental design

After identifying the most of influential parameters, the final phase is to verify the performance characteristics by conducting the confirmation experiments. The GRA with PCA and Taguchi analysis gives the optimal parameters combination as P3S2T3D1E3 for shot peening process of welded AISI 304 austenitic stainless steel.

Table 12: ANOVA results of grey relational grade.

Sourc	D	Seq SS	Adj	P	Contributi
P	2	0.0485	0.0242	0.00	11.78
S	2	0.0199	0.0099	0.02	04.83
T	2	0.1724	0.0862	0.00	41.86
D	2	0.0479	0.0239	0.00	11.65
E	2	0.0872	0.0436	0.00	21.16
Error	16	0.0358	0.0022		
Total	26	0.4119			
S = 0.0473432 R-Sq = 91.29%					

Hence this combination of shot peening parameters is used for confirmation tests. With these optimal settings the specimens give the surface hardness of 376VHN and impact strength of 252.41J.
The optimal grey relational grade (γ_{opt}) is predicted by using the following equation:

$$\gamma_{opt} = \gamma_m + \sum_{i=1}^{n} (\gamma_i - \gamma_m) \qquad (8)$$

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, nozzle distance and nozzle angle are all the significant parameters used for predicting the optimal grey relational grade.

Table 13: Experimental and predicted values of grey relational grade.

Performance characteristics	Predicted value	Experimental value
Optimal parameters	P3S2T3D1E3	P3S2T3D1E3
Surface hardness		376VHN
Impact strength		252.41J
Grey relational grade	0.8504	0.8071

The predicted value of optimal grey relational grade is expressed as:

$$\gamma_{opt} = \gamma_m + \sum_{i=1}^{5} (\gamma_i - \gamma_m)$$

For welded AISI 304 austenitic stainless steel the predicted value of optimal grey relational grade is calculated as:
=0.5563+(0.6519-0.5563)+(0.6237-0.5563)+(0.6140-0.5563) +(0.5918-0.5563)+(0.5942-0.5563) = 0.8504
It is found that calculated grey relational grade for these optimal values of performance characteristics is higher from the grey relational grade among the 27 experiments as shown in Table 13. This table also

represents that the grey relational grade for optimal parameters is near to the predicted value of optimal grey relational grade. Hence using the present approach, shot peening of welded AISI 304 austenitic stainless steel is successfully optimized.

8. Conclusion

This article has presented an investigation on the optimization of shot peening parameters on the surface hardness and impact strength of welded AISI 304 stainless steel. The significance of the parameters on surface hardness and impact strength is determined by using ANOVA. The response table and ANOVA presented in Table 11 and 12 shows that pressure, shot size, exposure time, nozzle distance and nozzle angle are the process parameters which significantly affecting the performance characteristics. All parameters affecting the performance characteristics are at 95% confidence level. The GRA with PCA and Taguchi analysis gives the optimal process parameters as P3S2T3D1E3. At this optimal condition the process parameters are set as: pressure 0.588MPa, shot size 1mm, exposure time 160 sec, nozzle distance 100mm and nozzle angle 90^0. At this level of process parameters the confirmatory experiments are performed and the average value of surface hardness and impact strength are measured as 376VHN and 252.41J respectively.

The calculated grey relation grade for these optimal values of performance characteristics is 0.8071 which is near to the predicted value of grey relational grade (0.8504) and above the grey relational grade among the 27 experiments i.e. 0.7745 Hence these are the proposed process parameter levels for the optimal shot peening process for welded AISI 304 austenitic stainless steel. It seems that GRA with PCA and Taguchi analysis is a straight forwarded method for optimizing multi performance characteristic problems in shot peening.

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