Regression analysis of shot peening process for performance characteristics of AISI 304 austenitic stainless steel

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ABSTRACT: *The surface fibers of the material are yielded in tension by the impact of shots in shot peening process. Below the surface fiber an even thin skin surface layer of material is deformed and this layer is highly stressed in compression. It results in the improvement of surface and mechanical properties of the material. Regression analysis is the statistical modeling technique, and it is suitable for the majority of predicting problems. It is valuable for quantifying the impact of various simultaneous influences upon a single dependent variable. In the present study quantification of performance characteristics were carried out, by developing the mathematical models of logarithmic nature using regression analysis. MINITAB 14 is a statistical tool which is used for the complete analysis. The analysis includes pressure, shot size, exposure time, nozzle distance and nozzle angle as process parameters. The complete analysis will be helpful to the manufacturer in deciding the shot peening parameters for desired performance characteristics. It helps the manufacturer to reduce the cost and improve its productivity.*

Keywords: *AISI 304 austenitic stainless steel, ANOVA, Regression analysis and Shot peening.*

I. Introduction

Stainless steel is iron-base alloys containing chromium and nickel. Chromium makes the surface passive by forming a surface oxide film [1, 2], which protects the underlying metal from corrosion. This is because when the metal is scratched; the oxide layer re-forms quickly, hence protecting it from corrosion. However, chromium is a ferrite stabilizer. To counteract this, nickel is added as an austenite stabilizer, so that the microstructure at ambient temperature remains as austenitic [3].The stainless steel attains its stainless characteristics due to the formation of an invisible and adherent chromium-rich oxide surface film. The austenitic stainless steel is used in verity of applications due to its corrosion resistance, ductility, good weldability and resistance to high and low operating temperatures [4]. The heat treatment processes make austenitic stainless steel soften. Further the addition of carbon results in sensitization. Austenitic stainless steel is usually cold worked to enhance the mechanical properties [5, 6, 7]. Kirk and Payne [5] concluded in their work that martensite formation was easily induced by plastic deformation in austenitic stainless steel.

Shot peening is a cold working process in which the surface of a part is bombarded with small spherical media with high speed called shot. Each shot striking the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. The surface fibers of the material are yielded in tension by the impact of shots. Below the surface fiber an even thin skin surface layer of material is deformed and this layer is highly stressed in compression. It develops a residual compressive stress in this thin skin surface layer [8, 9]. Shot peening is one of the most versatile tool to strengthen the metal parts against tensile strength, impact strength, surface hardness, compressive residual stress, damping, surface roughness, fatigue failure and corrosion. Shot peening is a well-known cold working process that affecting thin skin surface layer of the materials [10, 11, 12]. The layer is called the depth of deformed layer. The shot peening variables like shot material, shot quality, shot intensity, shot coverage etc. effect on mechanical properties [10, 13]. Kapoor and Tiwari [14] discussed some basic aspects of shot peening. They overviewed the shot peening process and mentioned its critical impacts. It is used now 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. [4].

The controlled shot peening parameters helps in enhancing the surface and mechanical properties of the material. T. Dorr et al. and M. Obata et al. discussed the increase in surface hardness and surface roughness with increase in shot size and the peening intensity [15, 16]. K.B. Prakash et al. have made study on shot peening for precision-machined steels with high strength to weight ratio [11]. As per the guidelines given by Champaine [13], the exposure time is an important factor to achieve desired peening coverage for the material.

The development of complex non-linear predictive model using regression analysis is well established approach to predict the performance characteristics. The researchers [17, 18] developed a mathematical model and the adequacy of the model was verified using ANOVA. Meguid et al. [19] developed a mathematical model for shot peening related to single and double impact events. Seceleanu et al. [20] pointed out the influence of some metallurgical factors on the phase transformation and properties of cast iron. They determined the mechanical properties of a S.G. cast iron and developed mathematical modeling using the regression analysis. Schiffner and Helling [21] constructed a simplified model to simulate the evolution of residual stress caused by shot peening. Delijaicov et al. [9] developed a mathematical model to describe the relationship between the shot peening process variables (shot diameter, impact velocity, static preload and coverage) and the curvature of the specimens made of aluminium 7050 and 7475 alloys.

The main objective of the present work is to investigate the effects of shot peening for improving the mechanical and surface properties of AISI 304 austenitic stainless steel. It is required to develop the mathematical models for multi performance characteristics of AISI 304 austenitic stainless steel. Therefore, an attempt was made in this study to find out the synergetic effect of different process parameters on performance characteristics. The investigation is helpful to the manufacturers for reduction of cost, performance variation and scrap to increase productivity.

II. Experimental set up

The material AISI 304 austenitic stainless steel is used for various tests. The composition of the material is shown in Table 1. The mechanical properties of the material are: tensile strength 617MPa, fatigue strength 228MPa and surface hardness 271VHN.

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

A 10mm thick flat plate was used for making various specimens for determining the tensile strength. The dimension of specimen for tensile strength test is shown in Fig. 2. These specimens were required to perform the tensile test at different process parameter levels.

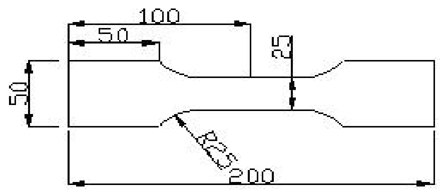
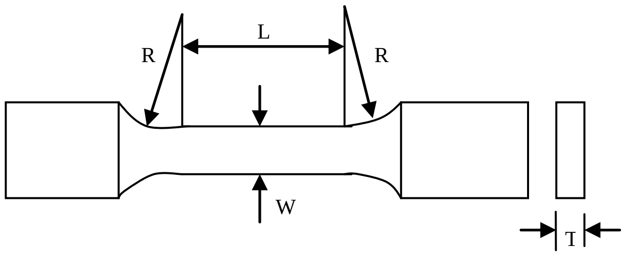


Fig. 2: Specimen for tensile test (all dimensions in mm).

Vickers hardness test was carried on the surface of specimens. The hardness measurements were performed on specimens of 20mm by 60mm by 10mm thickness using WOLPERT universal hardness testing machine dia tester – 2, model 2RC. The average values of three readings of surface hardness were taken for different peening parameters. The fatigue life of the USP and SP was tested by an axial fatigue-testing machine. Stress ratio (R) equal to 0.1 was used during fatigue testing.



T = 5mm W = 2.6T L = 3.23W R= 117 mm

Fig. 3: ASTM flat specimen for fatigue strength.

The dimension of specimen for plotting S-N curve is shown in Fig. 3. The dimensions of the specimens were according to the ASTM standards. Fifteen specimens were tested in order to plot an S/N curve. Only the average points were presented for each level. The specimens were testing in axial fatigue testing machine MTS model 810, at a frequency 30Hz, at room temperature. The other specifications of the machine are:

Type : Servo hydraulic system
Force Capacity : $\pm$ 285kN
Column space : 460 mm
Test space : 978mm

III. Selection of shot peening parameters

The selection of process parameters is most important step in Design of Experiments (DoE). Shot peening process constitutes a multiple impacts of small sized spherical balls onto a surface to achieve better surface and mechanical properties. In shot peening process the parameters are divided into two categories one is controlled before the start of the process i.e. shot size and 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 (θ) (considered in the analysis as sin θ i.e. impact of normal component of force) are the controllable influential process parameters under consideration. These shot peening parameters along with their levels are shown in Table 2.

Table 2: Process parameter and their levels

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	80	100	120
Nozzle Angle θ (Sin θ)	E	60^0 (0.866)	75^0 (0.966)	90^0 (1.000)

An air-blast shot peening machine was used for shot peening of the specimens. The hardness of shots was 56HRC to 60HRC.

IV. Design of experiments (DoE)

The DoE 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 tensile strength (TS), surface hardness (VHN) and fatigue strength (FS) are depicted in Table 3 for different 27 runs.

Table 3: Experimental results for different shot peening parameters.

Exp. No.	**P**	**S**	**T**	**D**	**E**	**TS**	**VHN**	**FS**
1	1	1	1	1	1	760.8	361.2	270.5
2	1	1	1	1	2	778.4	381.4	281.3
3	1	1	1	1	3	793.5	390.6	295.6
4	1	2	2	2	1	790.4	370.1	292.4
5	1	2	2	2	2	802.5	382.7	301.8
6	1	2	2	2	3	815.6	395.4	315.2
7	1	3	3	3	1	799.1	360.4	282.6
8	1	3	3	3	2	825.1	381.1	291.3
9	1	3	3	3	3	840.7	395.7	305.1
10	2	1	2	3	1	722.5	370.5	267.3
11	2	1	2	3	2	738.3	386.4	278.2
12	2	1	2	3	3	750.4	397.6	289.6
13	2	2	3	1	1	805.7	391.2	295.6
14	2	2	3	1	2	815.8	403.1	318.2
15	2	2	3	1	3	826.9	415.2	310.3
16	2	3	1	2	1	685.8	355.9	245.7
17	2	3	1	2	2	698.3	375.8	258.4
18	2	3	1	2	3	720.6	381.3	264.6
19	3	1	3	2	1	788.6	390.8	280.8
20	3	1	3	2	2	800.1	412.3	320.5
21	3	1	3	2	3	835.7	419.8	308.2
22	3	2	1	3	1	670.5	362.4	239.1
23	3	2	1	3	2	681.4	377.2	252.4
24	3	2	1	3	3	695.3	389.7	261.3
25	3	3	2	1	1	740.8	399.1	258.1
26	3	3	2	1	2	750.3	416.2	272.6
27	3	3	2	1	3	758.8	426.8	283.8

V. Regression analysis of performance characteristics

Regression analysis is a statistical tool to establish a mathematical relationship between the variables. The technique is helpful for the quantification of the performance characteristics. The present investigation involves the regression analysis of tensile strength, surface hardness and fatigue strength for AISI 304 austenitic stainless steel by using statistical software MINITAB 14. These models can be used for the selection of a set of shot peening parameter for desired performance characteristics.

The log transformed response variables are assumed for formulating the correlation. The following model is assumed for performance characteristics:

$$\ln(Y) = \beta_0 + \beta_1 \ln(P) + \beta_2 \ln(S) + \beta_3 \ln(T) + \beta_4 \ln(D) + \beta_5 \ln(E) \quad (1)$$

where Y is the performance characteristic and β_0, β_1, β_2, β_3, β_4, β_5 are the regression coefficients.

The log transformed response variables to formulate the correlation for AISI 304 austenitic stainless steel are shown in Table 4-5. Table 4 represents the log transformed response for process parameters and Table 5 represents log transformed response for performance characteristics.

5.1 Quantification of tensile strength

The quantification of each performance characteristic is established by regression analysis using statistical software MINITAB 14. The regression analysis outputs are tabulated in Table 6-8 for each performance characteristic. The regression results for tensile strength are shown in Table 6. It shows the following correlation between the tensile strength and the process parameters:

$$\ln(TS) = 6.27 - 0.0684 \ln(P) - 0.0265 \ln(S) + 0.178 \ln(T) - 0.114 \ln(D) + 0.249 \ln(E) \quad (2)$$

The exponential form of the equation is as follows:

$$(TS) = 528.47\ (P)^{-0.0684}\ (S)^{-0.0265}\ (T)^{0.178}\ (D)^{-0.114}\ (E)^{0.249} \quad (3)$$

Table 4: Log transformed response table for process parameters.

P	ln(P)	S	ln(S)	T	ln(T)	D	ln(D)	E	ln(E)
0.196	-1.6296	0.85	-0.1625	80	4.3820	80	4.3820	0.866	-0.1441
0.196	-1.6296	0.85	-0.1625	80	4.3820	80	4.3820	0.966	-0.0348
0.196	-1.6296	0.85	-0.1625	80	4.3820	80	4.3820	1.000	0.0000
0.196	-1.6296	1	0.0000	120	4.7875	100	4.6052	0.866	-0.1441
0.196	-1.6296	1	0.0000	120	4.7875	100	4.6052	0.966	-0.0348
0.196	-1.6296	1	0.0000	120	4.7875	100	4.6052	1.000	0.0000
0.196	-1.6296	1.85	0.6152	160	5.0752	120	4.7875	0.866	-0.1441
0.196	-1.6296	1.85	0.6152	160	5.0752	120	4.7875	0.966	-0.0348
0.196	-1.6296	1.85	0.6152	160	5.0752	120	4.7875	1.000	0.0000
0.392	-0.9365	0.85	-0.1625	120	4.7875	120	4.7875	0.866	-0.1441
0.392	-0.9365	0.85	-0.1625	120	4.7875	120	4.7875	0.966	-0.0348
0.392	-0.9365	0.85	-0.1625	120	4.7875	120	4.7875	1.000	0.0000
0.392	-0.9365	1	0.0000	160	5.0752	80	4.3820	0.866	-0.1441
0.392	-0.9365	1	0.0000	160	5.0752	80	4.3820	0.966	-0.0348
0.392	-0.9365	1	0.0000	160	5.0752	80	4.3820	1.000	0.0000
0.392	-0.9365	1.85	0.6152	80	4.3820	100	4.6052	0.866	-0.1441
0.392	-0.9365	1.85	0.6152	80	4.3820	100	4.6052	0.966	-0.0348
0.392	-0.9365	1.85	0.6152	80	4.3820	100	4.6052	1.000	0.0000
0.588	-0.5310	0.85	-0.1625	160	5.0752	100	4.6052	0.866	-0.1441
0.588	-0.5310	0.85	-0.1625	160	5.0752	100	4.6052	0.966	-0.0348
0.588	-0.5310	0.85	-0.1625	160	5.0752	100	4.6052	1.000	0.0000
0.588	-0.5310	1	0.0000	80	4.3820	120	4.7875	0.866	-0.1441
0.588	-0.5310	1	0.0000	80	4.3820	120	4.7875	0.966	-0.0348
0.588	-0.5310	1	0.0000	80	4.3820	120	4.7875	1.000	0.0000
0.588	-0.5310	1.85	0.6152	120	4.7875	80	4.3820	0.866	-0.1441
0.588	-0.5310	1.85	0.6152	120	4.7875	80	4.3820	0.966	-0.0348
0.588	-0.5310	1.85	0.6152	120	4.7875	80	4.3820	1.000	0.0000

5.2 Quantification of surface hardness

The regression analysis results for surface hardness are tabulated in Table 7. It shows the following correlation between the surface hardness and the process parameters:

$\ln(VHN) = 6.17 + 0.0427 \ln(P) - 0.00518 \ln(S) + 0.0826 \ln(T) - 0.114 \ln(D) + 0.479 \ln(E)$ (4)

The exponential form of the equation is as follows:

$(VHN) = 478.19\ (P)^{0.0427}\ (S)^{-0.00518}\ (T)^{0.0826}\ \ln(D)^{-0.114}\ (E)^{0.479}$ (5)

5.3 Quantification of fatigue strength

Similarly, the regression analysis results for fatigue strength are tabulated in Table 8. It shows the following correlation between the fatigue strength and the process parameters:

$\ln(FS) = 5.21 - 0.0599 \ln(P) - 0.0692 \ln(S) + 0.196 \ln(T) - 0.114 \ln(D) + 0.545 \ln(E)$ (6)

The exponential form of the equation is as follows:

$(FS) = 183.09\ (P)^{-0.0599}\ (S)^{-0.0692}\ (T)^{0.196}\ (D)^{-0.114}\ (E)^{0.545}$ (7)

The resulting regression analysis equations 3, 5 and 7 determine the values of tensile strength, surface hardness and fatigue strength of parent AISI 304 austenitic stainless steel. These mathematical models help in selecting the process parameters for the desired performance characteristics.

Table 5: Log transformed response table for performance characteristics.

TS	ln(TS)	VHN	ln(VHN)	FS	ln(FS)
760.8	6.6344	361.2	5.8894	270.5	5.6003
778.4	6.6572	381.4	5.9438	281.3	5.6394
793.5	6.6765	390.6	5.9677	295.6	5.6890
790.4	6.6725	370.1	5.9138	292.4	5.6783
802.5	6.6877	382.7	5.9473	301.8	5.7098
815.6	6.7039	395.4	5.9799	315.2	5.7532
799.1	6.6835	360.4	5.8872	282.6	5.6440
825.1	6.7155	381.1	5.9431	291.3	5.6744
840.7	6.7342	395.7	5.9807	305.1	5.7206
722.5	6.5827	370.5	5.9149	267.3	5.5885
738.3	6.6044	386.4	5.9569	278.2	5.6283
750.4	6.6206	397.6	5.9854	289.6	5.6685
805.7	6.6917	391.2	5.9692	295.6	5.6890
815.8	6.7042	403.1	5.9992	318.2	5.7627
826.9	6.7177	415.2	6.0288	310.3	5.7375
685.8	6.5306	355.9	5.8746	245.7	5.5041
698.3	6.5486	375.8	5.9291	258.4	5.5544
720.6	6.5801	381.3	5.9436	264.6	5.5782
788.6	6.6703	390.8	5.9682	280.8	5.6376
800.1	6.6847	412.3	6.0218	320.5	5.7699
835.7	6.7283	419.8	6.0398	308.2	5.7307
670.5	6.5080	362.4	5.8927	239.1	5.4769
681.4	6.5241	377.2	5.9328	252.4	5.5310
695.3	6.5443	389.7	5.9654	261.3	5.5657
740.8	6.6077	399.1	5.9892	258.1	5.5533
750.3	6.6205	416.2	6.0312	272.6	5.6080
758.8	6.6317	426.8	6.0563	283.8	5.6483

Table 6: Coefficients and intercepts for tensile strength

Predictor	Coef	SE Coef	T	P
Constant	6.2672	0.1055	59.43	0.000
ln(P)	-0.068376	0.007166	-9.54	0.000
ln(S)	-0.026452	0.009704	-2.73	0.013
ln(T)	0.17818	0.01143	15.59	0.000
ln(D)	-0.11445	0.01960	-5.84	0.000

ln(E)	0.24894	0.05294	4.70	0.000
S = 0.0168889 R-Sq = 95.0% R-Sq(adj) = 93.8%				

Table 7: Coefficients and intercepts for surface hardness.

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	6.16796	0.08756	70.44	0.000
ln(P)	0.042685	0.005949	7.17	0.000
ln(S)	-0.005179	0.008057	-0.64	0.527
ln(T)	0.082557	0.009490	8.70	0.000
ln(D)	-0.11442	0.01627	-7.03	0.000
ln(E)	0.47902	0.04396	10.90	0.000
S = 0.0140223 R-Sq = 93.4% R-Sq(adj) = 91.8%				

Table 8: Coefficients and intercepts for fatigue strength

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	5.2125	0.1373	37.96	0.000
ln(P)	-0.059897	0.009331	-6.42	0.000
ln(S)	-0.06917	0.01264	-5.47	0.000
ln(T)	0.19636	0.01488	13.19	0.000
ln(D)	-0.11358	0.02552	-4.45	0.000
ln(E)	0.54518	0.06894	7.91	0.000
S = 0.0219920 R-Sq = 94.0% R-Sq(adj) = 92.5%				

VI. Discussion and validation

ANOVA, R-sq value and R-sq (adj) value are used for the validation of the models obtained by regression analysis. The ANOVA is the statistical treatment applied to determine the significance of the regression model. The R-sq is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It is the proportion of variability in a data set that is accounted for by the statistical model. It gives the information about goodness of fit for a model. In regression, the R-sq is a statistical measure of how well the regression line approximates the real data points. An R-sq of 1.0 indicates that the regression line perfectly fits in the data. Unlike R-sq, an R-sq (adj) allows for the degrees of freedom associated with the sums of the squares. Therefore, even though the residual sum of squares decreases or remains the same as new independent variables are added, the residual variance does not. For this reason, R-sq (adj) is generally considered to be a more accurate goodness-of-fit measure than R-sq. R-sq (adj), is a modification of R-sq that adjusts for the number of explanatory terms in the model.

The results of ANOVA, R-sq and R-sq (adj) are obtained by regression analysis using MINITAB 14 and are shown in the following sections. The results show the significance of the analysis. It is observed from Tables 9-11 that p-values for the response tensile strength, surface hardness and fatigue strength is less than 0.05, which shows that it is at 95% confidence level. R-sq is the statistical measure of the exactness at which the total variation of dependent variables is explained by regression analysis. The obtained values of R-sq and R-sq (adj) (Table 6-8) are more than 0.90 and quite near to 1.0 for the performance characteristics, it indicate a good fit. This confirms that the model adequately describes the observed data.

Table 9: ANOVA for tensile strength

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	5	0.113433	0.022687	79.54	0.000
Residual Error	21	0.005990	0.000285		
Total	26	0.119423			

Table 10: ANOVA for surface hardness

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	5	0.058154	0.011631	59.15	0.000
Residual Error	21	0.004129	0.000197		
Total	26	0.062283			

Table 11: ANOVA for fatigue strength

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	5	0.158428	0.031686	65.51	0.000
Residual Error	21	0.010157	0.000484		
Total	26	0.168584			

VII. Conclusion

Logarithmic regression models for shot peened AISI 304 austenitic stainless steel properties with a wide scope have been developed and can help the engineers with relative success in future. These models are tested with various experiments to investigate how the different inputs influenced the mechanical behaviour. Analysis shows good agreement with the literature. Hence the models are considered to be a good reflection of properties of shot peened AISI 304 austenitic stainless steel. MINITAB 14, the response optimizer is used for maximizing the response based on the selected regression model. All analysis results, including, best parameter level combinations, 95% confidence intervals, R-sq and R-sq (adj) of the regression models are estimated. The best chosen regression models for AISI 304 austenitic stainless steel are shown in equations 3, 5 and 7 for tensile strength, surface hardness and fatigue strength respectively. Regression models correlating tensile strength, surface hardness and fatigue strength with process parameters have obtained with R-sq and R-sq (adj) value more than 0.90. The results obtained for optimum process parameters by these equations are near to the experimental values. Hence equations provide a useful guide for setting proper values of process parameters so as to obtain desired tensile strength, surface hardness and fatigue strength.

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