Int J Adv Manuf Technol (2008) 38:563–574
DOI 10.1007/s00170-007-1222-6

ORIGINAL ARTICLE

Effect of shot peening parameters on microhardness of AISI 1045 and 316L material: an analysis using design of experiment

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Received: 2 January 2007 / Accepted: 28 August 2007 / Published online: 19 September 2007

Abstract Shot peening is widely used to improve the fatigue properties of components and structures. Residual stresses, surface roughness, and work hardening are the main beneficial effects induced in the surface layer from shot peening, which depend on the correct choice of the peening parameters. In this investigation, experiments were designed using the full factorial design of experiment (DOE) technique and an air blast type of shot peening machine. Effects of process parameters such as pressure, shot size, stand-off distance, and exposure time on surface microhardness for AISI 1045 and 316L materials were investigated. An ANOVA was carried out to identify the significant peening parameters. In the case of 316L material, the maximum surface hardness was found to be in the range of 450–824 Hv, whereas it was found to be in the range of 314–360 Hv for AISI 1045. A critical assessment was made so as to understand the variation of microhardness in the direction of peening. Empirical equations between the peening parameters and the surface microhardness for both materials were developed, which are useful in predicting the surface microhardness. It is believed that this technique could prove beneficial in industries for reduction of performance variation and cost and to increase productivity.

Keywords Cold work · Microhardness · Shot peening parameters · DOE · ANOVA

Originally presented in December 2006 at the 22nd AIMTDR Conference at IIT Roorkee, India.

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1 Introduction

Shot peening, which is a surface enhancement technique, has widespread applications in automobile, aircraft, and marine industries. It is a cold-working process that hardens the surface of a metallic component by bombarding it with a stream of small particles called shots. The process induces a state of compressive residual stress at the material surface and the cold working. Benefits from shot peening can be attributed to the compressive stresses and the cold working induced in the surface. Compressive stresses are beneficial in increasing resistance to fatigue failure, corrosion fatigue, stress corrosion cracking, hydrogen assisted cracking, fretting, galling, and erosion caused by cavitations. Benefits obtained due to cold working include work hardening, intergranular corrosion resistance, closing of porosity, and testing the bond of coatings.

The quality of peening is determined by the degree of coverage, magnitude and depth of the induced residual stress [1–4]. Various studies have demonstrated the improvements induced by the peening process; thus, it can be widely used to enhance the life of components operating in highly stressed environments and other critical parts such as in motor racing, aero engines and aero structures [5, 6].

The surface modifications produced by the shot peening treatment are: (a) roughening of the surface, (b) an increased near-surface dislocation density (strain hardening), and (c) the development of a characteristic profile of residual stresses [7]. However, low surface roughness increases fatigue strength as a result of higher dislocation densities near the surface due to the increase in surface hardness [8]. An increase in microhardness and surface roughness increases with increase in shot size and the peening intensity [9, 10]. Surface roughness in stainless steel bead peening is lower than that with glass bead and also in some cases it is

Table 1 Chemical composition of 316L steel

Element	Wt%
Carbon	0.03
Silicon	0.75
Manganese	2.0
Sulphur	0.03
Phosphorous	0.045
Chromium	17
Molybdenum	2.9
Nickel	14
Ferrous	Bal.

found that the surface roughness is roughly proportional to surface hardness [11].

Review of the literature shows that several authors have used one-factor-at-a-time experiments in analyzing surface roughness and microhardness behavior with different peening parameters such as peening intensity [9], types of shot [12], shot size [13], shot velocity [14] and impact angle [15]. Most authors have used traditional methods to study the effect of shot peening parameters on surface roughness [2], surface hardness, and wear [16]. Only a few authors have used the design of experiment (DOE) technique with a specialized single-ball controlled shot peening machine [17]. Design for robust fatigue performance with the help of the simulation technique has also been investigated [18]. In view of this, it is necessary to carry out comprehensive investigations using DOE technique so as to evaluate the effect of process parameters such as pressure, shot size, exposure time, and nozzle distance and their interactions on surface integrity aspects such as surface microhardness of the material.

Wear resistance of the component can be increased by controlling surface roughness, whereas fatigue life can be enhanced by increasing the cold work and thereby the surface hardness. Depending on the applicability of the component for fatigue and/or wear, the surface can be controlled by setting proper levels of the peening parameters based on their individual as well as interaction effects.

Several authors have carried out shot peening studies on precision-machined steels with high strength to weight ratio [19]; such steels are typically used for various components in aircraft, turbine, and defense equipment. It is noted that hardly any shot peening studies have been made for fatigue performance of conventional materials using the DOE technique. Further, no study with respect to surface microhardness appears to have been made to date. To bring this technique down to the ground level applications, the present study focuses on shot peening of conventional materials using an air blast shot peening (SP) machine. Hence, AISI 1045 and 316L materials were selected as work materials in the present study since they are used in automobile and marine engine applications.

Table 2 Chemical composition of AISI 1045 steel

Element	Wt%
Carbon	0.43
Silicon	0.26
Manganese	0.78
Sulphur	0.033
Phosphorous	0.028
Ferrous	Bal.

Table 3 Chemical composition of shots

Element composition	Shot type and diameter	
	S-390(1 mm)	S-660(1.85 mm)
Carbon	0.94	0.91
Silicon	0.75	0.7
Manganese	0.81	0.77
Sulphur	0.042	0.044
Phosphorous	0.047	0.047

2 Experimental analysis

2.1 Selection of materials

Experiments were conducted on turned specimens made of low carbon steel 316L and medium carbon steel AISI 1045. The average value of initial surface hardness (Vicker's hardness) for 316L and AISI 1045 specimens was 264 and 187 Hv, respectively. For both the specimens, the average value of initial surface roughness (Ra) was in the range of 4 to 5 μm. The chemical composition of these materials is given in Tables 1 and 2. These materials were selected since they are widely used in marine and automobile applications.

2.2 Selection criteria for the shot peening parameters

The shot peening process relies on multiple impacts of spherical media onto a surface to achieve better surface hardness and fatigue life. The various shot peening parameters are shot type and size, intensity, saturation, incidence

Table 4 Factor levels for the experiment

Factors	Lower level-1	Higher level-2
P: pressure (kg/cm^2)	2	4
S: shot type	S-390 (1 mm diameter)	S-660 (1.85 mm diameter)
T: exposure time (s)	80	160
D: nozzle distance (mm)	80	100

Table 5 Full factorial design matrix

Std. order trial no.	Pressure	Shot type	Exposure time	Nozzle distance	Average response of replications (Y) of surface hardness (Hv)	
					AISI 1045	316L
1	1	1	1	1	285	528
2	1	1	1	2	303	453
3	1	1	2	1	309	366
4	1	1	2	2	360	464
5	1	2	1	1	316	488
6	1	2	1	2	297	366
7	1	2	2	1	336	476
8	1	2	2	2	316	431
9	2	1	1	1	309	309
10	2	1	1	2	336	528
11	2	1	2	1	344	351
12	2	1	2	2	245	401
13	2	2	1	1	359	824
14	2	2	1	2	210	366
15	2	2	2	1	351	431
16	2	2	2	2	344	431

angle, velocity, and coverage. Among these parameters, only shot type and incidence angle are controlled directly. The remaining parameters are measured or evaluated, in most cases, after peening is complete. The variables that can be controlled and adjusted to obtain the desired values of intensity, saturation, and coverage are air pressure, shot mass flow rate, nozzle type, feed rate of the nozzle along the work piece, distance of the nozzle from the work piece, and the work piece table speed. Since some parameters such as velocity, intensity, and coverage are difficult to control, controllable influential parameters such as pressure, shot size, nozzle stand-off distance, and exposure factors were considered in the present investigation.

As per the guidelines given by Champaine [20], the exposure time to achieve desired peening coverage for the material was determined by 10X-magnifying lenses. Almen strips were not used since Almen strip saturation time can be misleading due to the surface hardness difference between the Almen strip and the peening material [20, 21].

Table 6 Estimates of main factors

Main factors	Effects on surface hardness (Hv)	
	AISI 1045	316L
Pressure	−3.000	8.625
Shot type	4.750	51.625
Nozzle distance	23.750	−63.875
Exposure time	−24.750	−41.625

Table 7 Estimates of two-way factors

Two-way interaction factors	Two-way interaction effects (Hv)	
	AISI 1045	316L
Pressure–shot type (P–S)	−15.875	6.875
Pressure–nozzle distance (P–D)	−6.250	−39.375
Pressure–exposure time (P–T)	−32.250	−5.625
Shot type–nozzle distance (S–D)	17.500	−4.875
Shot type–exposure time (S–T)	−24.000	−114.625
Nozzle distance–exposure time (D–T)	6.000	67.375

The experiments were conducted by using steel shots S-660 and S-390. The selection was based on MIL-S-13165B specifications [22] and the surface conditions of the specimen. According to the test certificates from the manufacturer, the shots were tested and sieve analysis was done as per IS 4606 of 1983 (Table 3).

2.3 Design of experiment

Preliminary (screening) experiments were conducted so as to identify the suitable process parameters and their levels [23]. These experiments revealed that magnitude of pressure greater than 4 kg/cm^2 (4.053 bars) resulted in greater surface roughness and hardness, which, in turn, caused about four-fold reduction in fatigue life compared to the unpeened component. A similar trend was observed when excessive exposure time and larger shot size were used. On the other hand, pressure less than 2 kg/cm^2 (2.026 bars) was found to result in clogging of shots due to lower suction of pressurized air, which, in turn, induced lesser cold work and coverage.

Table 8 Effects of three- and four-way factors

Type of interaction factor	Effects	
Three-way interaction factors	Three-way interaction effects (Hv)	
	AISI 1045	316L
PSD	28.000	−55.875
PST	3.000	−67.125
PDT	−2.000	4.875
SDT	29.250	66.375
Four-way interaction factor	Four-way interaction effect (Hv)	
	AISI 1045	316L
PSDT	37.750	90.375
Maximum and minimum responses (*Y*) (Hv)		
Y average	313.750	450.813
Y maximum	341.875	461.188
Y minimum	285.625	440.438

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

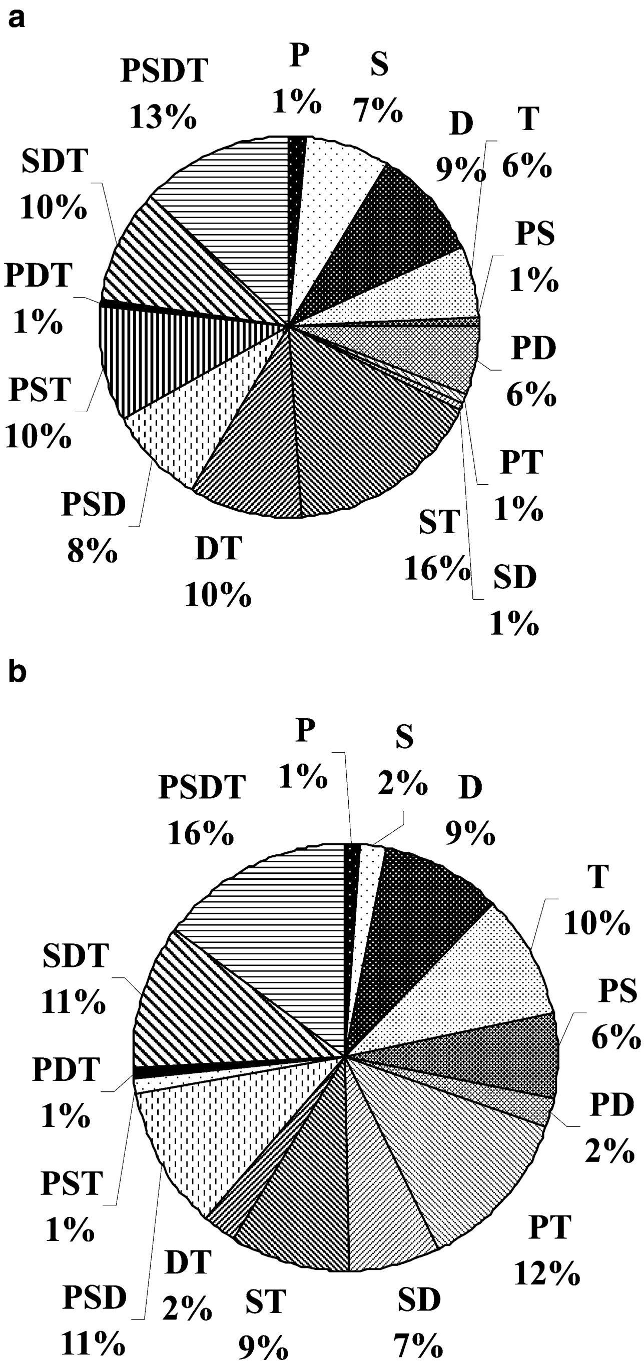


Fig. 1 **a** Parameters and their interaction effects on surface hardness for 316L. **b** Parameters and their interaction effects on surface hardness for AISI 1045

The above findings were used as the basis for selection of the process parameters and their levels as shown in Table 4. The following factors were held constant: jet obliquity equal to 90° and symphonic nozzle orifice diameter of 9 mm.

The design of experiment was based on 2^k full factorial design considering four factors each at two levels. In order to reduce process and product variability, the sixteen runs of the experiment were replicated twice. The design matrix considering two replicates is shown in Table 5. The microhardness (Hv) for each peened specimen was measured by using Vickers microhardness testing machine type MVH-1 with a test load of 0.98 N and dwell period of 10 s. The average of the replications of surface hardness values for each trial are shown in Table 5. The effect of each main factor and all the interactions were calculated as per the methodology given by Lochner and Matar [24] and are as shown in Tables 6, 7 and 8.

3 Results and discussion

The data from Tables 6, 7 and 8 were used to draw pie charts as shown in Fig. 1 and the graphical representations in Fig. 2. Figure 1a,b shows a pie chart indicating the interaction effects of the four main factors (P pressure, S shot size, T exposure time, and D nozzle distance), as well as their two-, three-, and four-way interactions on the surface hardness. In both cases, the contributions of pressure and nozzle distance were the same; however, significant difference can be observed when two- and three-way interactions were compared. In 316L material, the interaction effects between P-T and S-D were negligible, but these effects were significant in AISI 1045 material.

Out of the four main factors, the dominant factors for both materials were the nozzle distance, shot size, and exposure time. But compared to the two-way and other interactions, it was found that no main factor was significant individually.

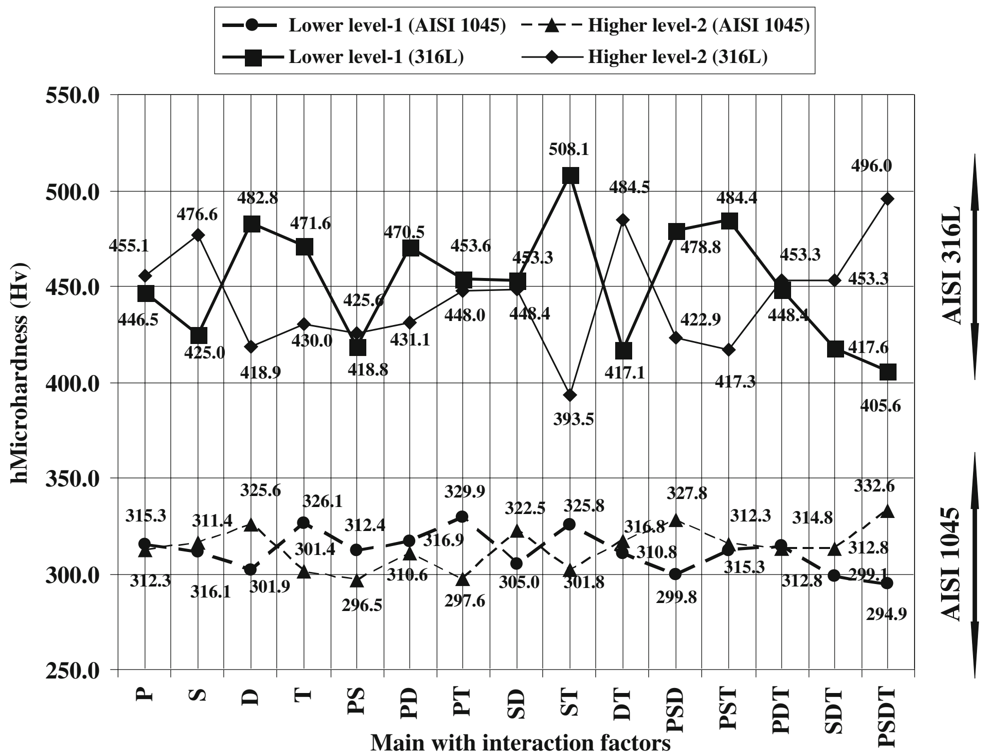
For the purpose of analyzing the effects of main factors and interactions on the surface hardness, the two-way interaction effects of T-D, S-P, D-S, D-P, T-P, and T-S were plotted separately as shown in Figs. 3, 4, 5, 6, 7 and 8. These plots are based on the data given in Table 5 taking the average value of each factor at their higher and lower levels.

The maximum and minimum response values for the surface hardness were calculated by adding individual contributions of the main factors to the grand mean (Table 8).

3.1 Effect on 316L material

The maximum value of surface hardness from Table 5 is 824 Hv, which occurred when pressure and shot size were set at higher levels and the other two at lower levels. According to Fig. 2, the maximum value can be obtained by setting parameter shot size and pressure at higher levels, and the exposure time and nozzle distance at lower levels. Again, by considering interaction effects from Figs. 4, 6 and 7, the pressure and shot size can be set to higher levels. By setting pressure and shot size at higher levels and the other factors at lower levels, confirmation

Fig. 2 Graphical display of effects



tests were carried out and the maximum surface hardness was found to be in the range of 461–824 Hv.

From the analysis of interaction effect on surface hardness from Fig. 5, it was found that hardness value increased with increase in shot size as well as with the decrease in nozzle distance. This is because the two line segments are almost parallel, implying no interaction between shot size and nozzle distance. From Figs. 3 and 7, it was observed that keeping the exposure time at its lower level, the hardness value increases with decrease in nozzle distance and increase in pressure.

The line segments in Figs. 3, 4, 6, 7 and 8 are not parallel and are intersecting. This indicates the presence of strong interactions between T-D, S-P, D-P, T-P and T-S. However, it is interesting to note that with the use of smaller shot size, the microhardness increased with the decrease in pressure, but with the larger size shot it increased with increase in

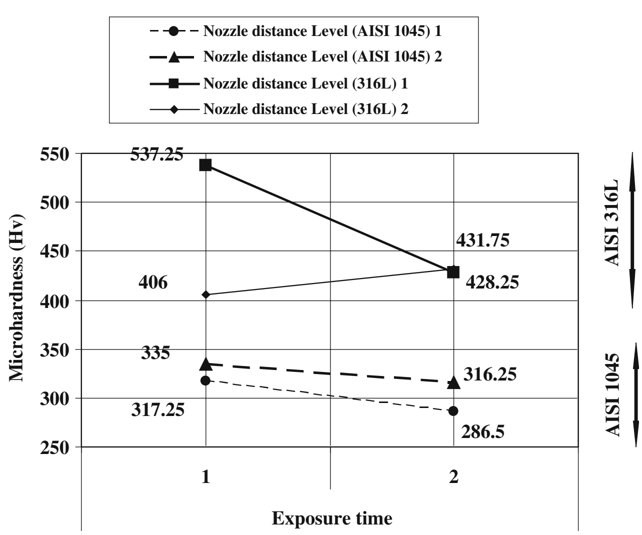


Fig. 3 Interaction between exposure time and nozzle distance

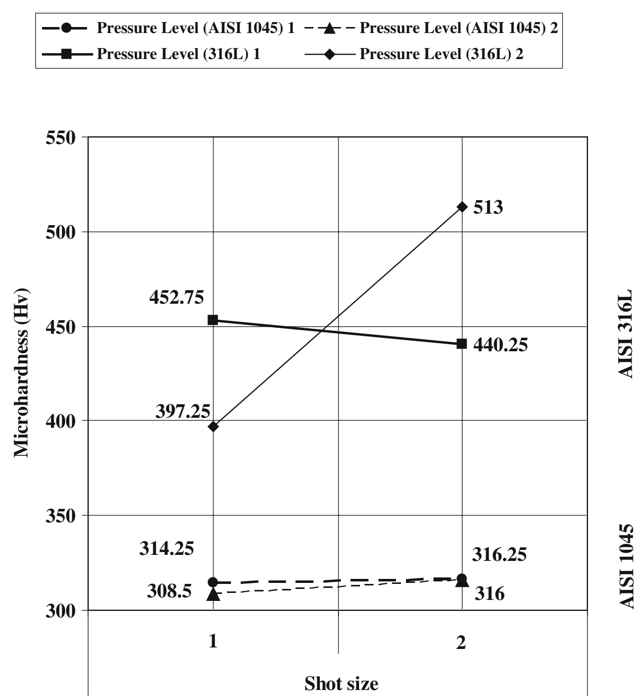


Fig. 4 Interaction between shot size and pressure

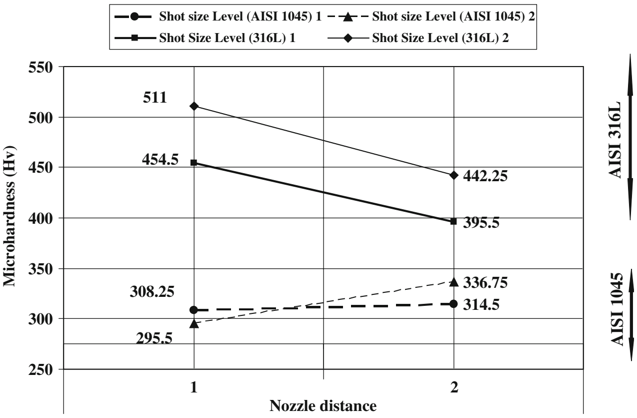


Fig. 5 Interaction between nozzle distance and shot size

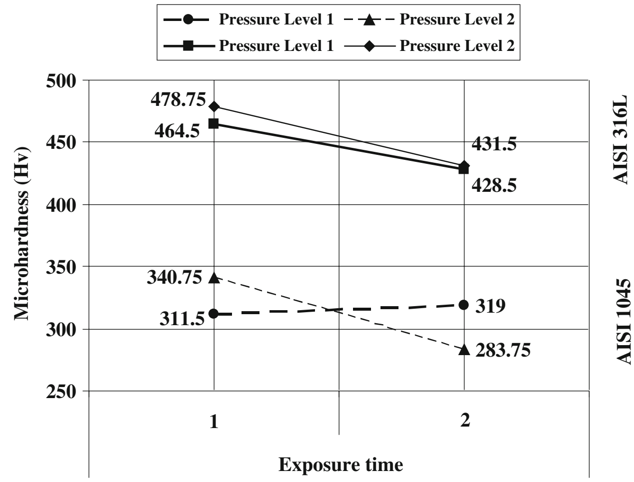


Fig. 7 Interaction between exposure time and pressure

pressure (Fig. 4). Again, for the smaller nozzle distance, surface hardness increased with increased pressure but at a greater distance it increased with decrease in pressure (Fig. 6).

The surface deformation characteristic depends mainly on the shot size, nozzle distance, and the exposure time. Since the initial surface microhardness for the 316L material is more when compared to AISI 1045 material, the surface deformation much depends on the exposure time and the nozzle distance rather than the shot size subjected to the same condition of peening.

3.2 Effect on AISI 1045 material

The maximum value of surface hardness from Table 5 is 360 Hv, which occurred when pressure and shot size were set at their lower levels and the other two at higher levels. According to Fig. 2, the maximum value can be obtained by setting the parameters shot size and nozzle distance at higher levels, and the exposure time and pressure at lower levels. Again, by considering the interaction of shot size with other factors (Figs. 4, 5 and 8), shot size can be set to its higher level. By setting parameters S and D at higher levels and the other two at lower levels, confirmation tests were carried out and the maximum surface hardness was found to be in the range of 342–360 Hv.

From the analysis of interaction effects on surface hardness from Fig. 5, it was found that hardness increased with increase in shot size; however, for lower nozzle distance hardness increases with decrease in shot size, but at higher nozzle distance it increases with the increase in shot size. The two line segments are not parallel. Hence, it indicates the presence of a strong interaction between shot size and nozzle distance. From Fig. 3, it was observed that keeping the nozzle distance constant, the hardness value increased with decrease in the exposure time. For a lower pressure level, hardness increased with an increase in pressure; however, by doubling the exposure time it decreased (Fig. 7).

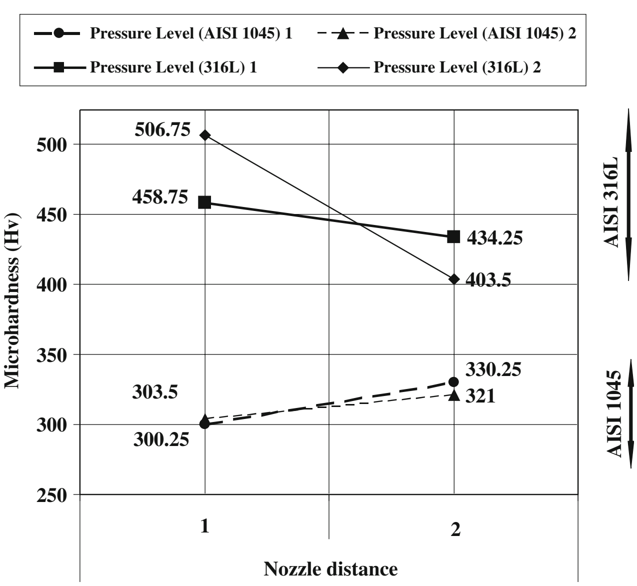


Fig. 6 Interaction between nozzle distance and pressure

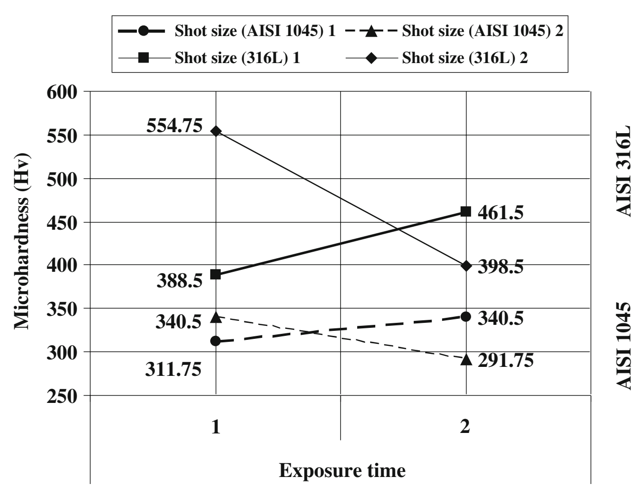


Fig. 8 Interaction between exposure time and shot size

Table 9 Peening parameters and their levels

Material	Pressure (kg/cm^2)	Shot size (mm)	Nozzle distance (mm)	Exposure time (s)
AISI 1045	2	1.85	100	80
316L	4	1.85	80	80

The line segments in Figs. 4, 5, 6, 7 and 8 are not parallel and are intersecting. Hence, it indicates the presence of strong interaction between S-P, D-S, D-P, T-P, and T-S. However, it is interesting to note that with the use of smaller shot size, the microhardness increased with the decrease in pressure, but this trend of increase in hardness decreased with the use of larger shot size (Fig. 4). Again for the lower nozzle distance, surface hardness increased with increase pressure but at larger distance it increased with decrease in pressure (Fig. 6).

Interaction between exposure time and shot size was significant in the case of 316L material (Fig. 8); whereas in the case of AISI 1045 the interaction effect between pressure and exposure time was significant (Fig. 7). These differences in the interaction effects were due to the change in the plastic deformation characteristics of the peened material.

3.3 Study of variation of microhardness

The investigation in the distribution of microhardness beneath the peened surface was based on the peening parameters which are set at maximum surface hardness condition. For this purpose two specimens were prepared and were peened under the conditions shown in Table 9. The levels for both the materials were based on the criteria of the maximum microhardness condition obtained from the 2^k full factorial experimentation work.

Experiments were conducted on turned specimens made of medium carbon steel AISI 1045 and 316L materials. The initial surface hardness for the specimens was measured and found to be 187 Hv for AISI 1045 material and 264 Hv for 316L material. In order to evaluate the variation of the microhardness, two specimens were shot peened as per the conditions given in Table 9. These shot peened components were cut at an angle 90° to the specimen axis by using an abrasive wheel cutting machine incorporated with a proper coolant system. The specimen mounting was prepared with the combination of cold setting plastic powder and cold setting liquid (LP-22). The hardness readings were taken by using Vickers microhardness testing machine MVH-1 with a test load of 0.98 N and a dwell period of 10 s (Table 10).

Table 10 Variation of microhardness for AISI 1045 and 316L material

Depth in μm	Microhardness (Hv) for AISI 1045	Microhardness (Hv) for 316L
0	338	818
120	310	608
300	283	456
500	267	412
700	253	321
900	232	304
1000	221	272

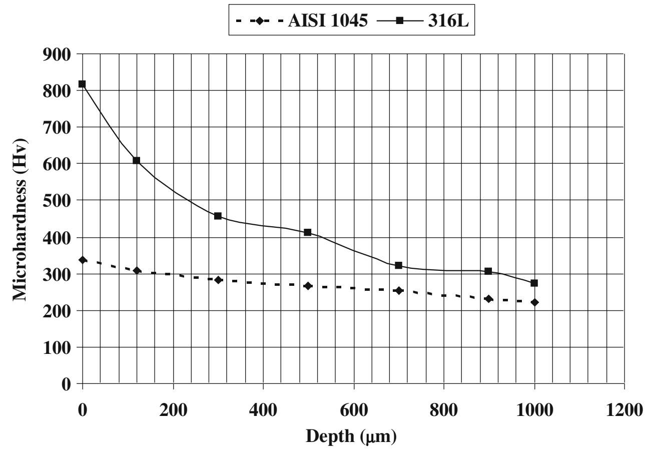


Fig. 9 Distribution of microhardness across the depth

In both cases, it was observed that the surface microhardness was more at the surface and gradually decreased as the depth increases (Fig. 9). However, in 316L material the decreasing trend with the depth was much steeper than with AISI 1045 material. Since AISI material is softer than the 316L material, plastic deformation in this material is greater compared to 316L. This, in turn, induces more cold work resulting in greater hardness compared to its core hardness (187 Hv).

The microhardness values for 316L at the surface are greater compared to the values obtained for the AISI 1045 material. This can be attributed to the fact that the microhardness increases with the decrease in the nozzle distance, which ultimately increases the cold work. It is interesting to note that the hardness value is still more than the core hardness at the depth of 1,000 μm.

4 Analysis of variance

Analysis of variance (ANOVA) is used to judge whether or not the experimentally found significant factors are statistically significant. In the present investigation, MINITAB (statistical software) was used to analyze the significance of factors. The significance can also be judged by calculating F or P values. Furthermore, the calculated F values (product

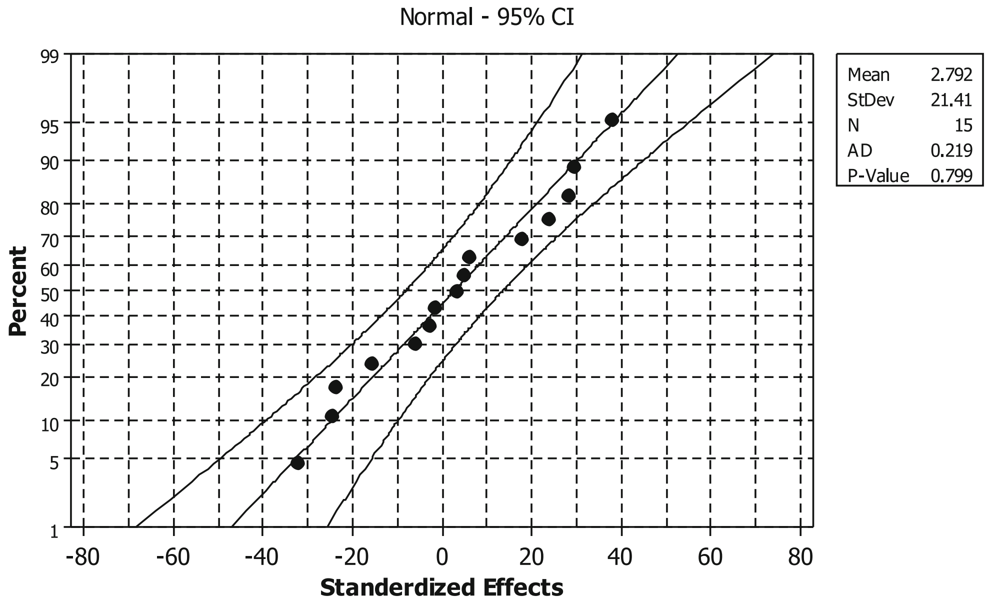


Fig. 10 Normal probability plot of residuals for AISI 1045

of the square of the effect and the degrees of freedom) are compared with the theoretical extreme values for the F distribution [24].

In ANOVA, the meaning of 5% significance level implies 1 in 20 and 1% means 1 in 100. This indicates that the parameters falling in 1% significance level are the most dominant factors and those of 5% significance are the next dominant factors.

Normal distribution plots (Figs. 10 and 11) are used to identify the outlier points most likely to represent real factor effects. The points/estimates which are close to the line fitted to the middle group of points represent estimated factor effects which do not demonstrate any significant effects on the response variable [24].

4.1 ANOVA for AISI 1045

From ANOVA (Table 11), it is can be seen that the most dominating factors among the main factors are exposure time and nozzle distance, because these parameters have higher F-statistic values. Among the two-way interactions, the interaction between shot size and exposure time (P-T) is more significant and the next interaction effects in decreasing order are S-T, S-D, P-D, D-T, and P-S.

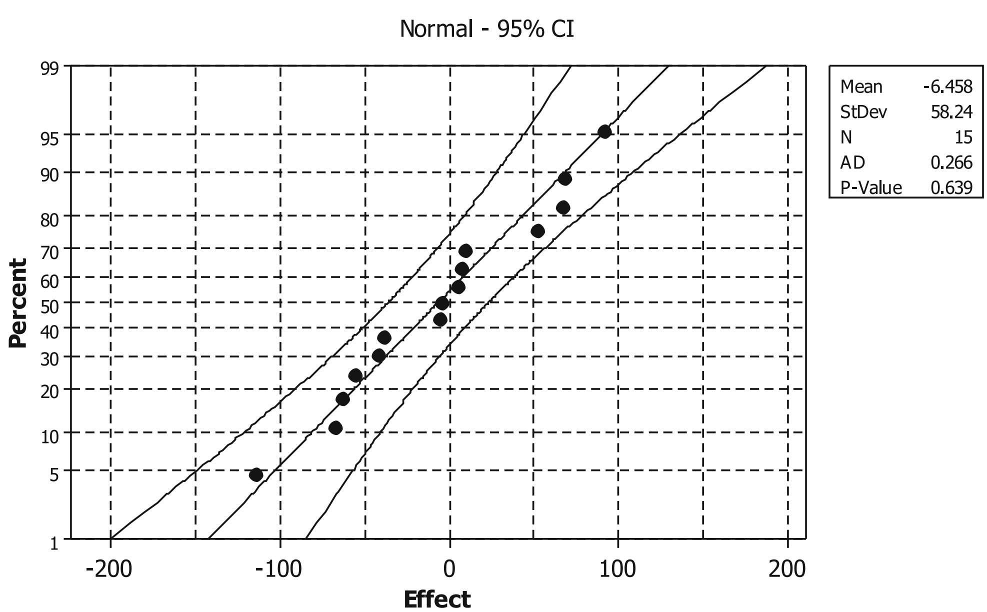


Fig. 11 Normal probability plot of residuals for 316L

Table 11 Analysis of variance using adjusted SS tests (AISI 1045)

Source	DF	Esq SS	Adj SS	Adj MS	*F*	*P*
P	1	72.0	72.0	72.0	6.78	0.019
S	1	180.5	180.5	180.5	16.99	0.001
D	1	4,512.5	4,512.5	4,512.5	424.71	0.000
T	1	4,900.5	4,900.5	4,900.5	461.22	0.000
PS	1	60.5	60.5	60.5	5.69	0.030
PD	1	312.5	312.5	312.5	29.41	0.000
PT	1	8,320.5	8,320.5	8,320.5	783.11	0.000
SD	1	2,450.0	2,450.0	2,450.0	230.59	0.000
ST	1	4,608.0	4,608.0	4,608.0	433.69	0.000
DT	1	288.0	288.0	288.0	27.11	0.000
PSD	1	6,272.0	6,272.0	6,272.0	590.31	0.000
PST	1	72.0	72.0	72.0	6.78	0.019
PDT	1	32.0	32.0	32.0	3.01	0.102
SDT	1	6,844.5	6,844.5	6,844.5	644.19	0.000
PSDT	1	11,400.5	11,400.5	11,400.5	1,072.99	0.000
Error	16	170.0	170.0	170.0		
Total	31	50,496.0	50,496.0	50,496.0		

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

Results from the ANOVA test show that all the main factors except pressure are statistically significant at a significance level of 1%, since the *p*-values for these parameters are less than 0.01 and the significance level for pressure is 5%. These values agree with the normal probability plot (Fig. 10).

4.2 ANOVA for 316L

From the ANOVA results for 316L (Table 12), it can be seen that the most dominating factor among the main factors is nozzle distance (D), since it has a higher *F*-statistic value. The next dominating parameters are shot size (S), exposure time (T), and pressure (P). The *p*-value for each of the main factors is less than 0.01, which indicates that all the factors are significant at 1% significance level.

Among the two-way interactions, the interaction between shot size and the exposure time (S-T) is the most significant. The next most significant interaction effects in decreasing order are D-T, P-S, P-D, P-T, and S-D. The *p*-value for the interaction S-D is more than 0.05, which indicates that it is not significant. This is also observed in the normal probability plot (Fig. 11).

Table 12 Analysis of variance using adjusted SS tests (316L)

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
P	1	595	595	595	31.53	0.000
S	1	21,321	21,321	21,321	1129.60	0.000
D	1	32,640	32,640	32,640	1729.328	0.000
T	1	13,861	13,861	13,861	734.36	0.000
PS	1	32,896	32,896	32,896	1,742.84	0.000
PD	1	12,403	12,403	12,403	657.12	0.000
PT	1	253	253	253	13.41	0.002
SD	1	190	190	190	10.07	0.006
ST	1	105,111	105,111	105,111	5,568.80	0.000
DT	1	36,315	36,315	36,315	1,923.98	0.000
PSD	1	24,976	24,976	24,976	1,323.24	0.000
PST	1	36,046	36,046	36,046	1,909.73	0.000
PDT	1	190	190	190	10.07	0.006
SDT	1	35,245	35,245	35,245	1,867.29	0.000
PSDT	1	65,341	65,341	65,341	3,461.78	0.000
Error	16	302	302	19		
Total	31	417,687				

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

Table 13 Log transformed parameters for 2^k design matrix

Trial number	*P*	ln (*P*)	*S*	ln (*S*)	*D*	ln (*D*)	*T*	ln (*T*)
1	2	0.693	1	0	80	4.382	80	4.382
2	2	0.693	1	0	80	4.382	160	5.075
3	2	0.693	1	0	100	4.605	80	4.382
4	2	0.693	1	0	100	4.605	160	5.075
5	2	0.693	1.85	0.615	80	4.382	80	4.382
6	2	0.693	1.85	0.615	80	4.382	160	5.075
7	2	0.693	1.85	0.615	100	4.605	80	4.382
8	2	0.693	1.85	0.615	100	4.605	160	5.075
9	4	1.386	1	0	80	4.382	80	4.382
10	4	1.386	1	0	80	4.382	160	5.075
11	4	1.386	1	0	100	4.605	80	4.382
12	4	1.386	1	0	100	4.605	160	5.075
13	4	1.386	1.85	0.615	80	4.382	80	4.382
14	4	1.386	1.85	0.615	80	4.382	160	5.075
15	4	1.386	1.85	0.615	100	4.605	80	4.382
16	4	1.386	1.85	0.615	100	4.605	160	5.075

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

5 Quantification of surface hardness for AISI 1045 and 316L material

Correlations for surface microhardness of both the materials were obtained by developing regression models using Analyze-it software (Microsoft). For this analysis, a log transformed response variable and process parameters were assumed and are tabulated as shown in Tables 13 and 14. For better curve fitting, the following model was assumed:

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

Table 14 Log transformed responses for 2^k design matrix

Responses for AISI 1045		Responses for 316L	
Hv	ln (Hv)	Hv	ln (Hv)
285	5.652	528	6.269
303	5.713	453	6.116
309	5.733	366	5.902
360	5.886	464	6.139
316	5.755	488	6.190
297	5.694	366	5.902
336	5.817	476	6.165
316	5.756	431	6.066
309	5.733	309	5.733
336	5.817	528	6.269
344	5.840	351	5.860
245	5.501	401	5.994
359	5.883	824	6.714
210	5.347	366	5.905
351	5.861	431	6.066
344	5.841	431	6.066

where β_1, β_2, β_3, and β_4 are the regression coefficients to be determined and Y is the surface hardness (Hv).

5.1 Quantification for AISI 1045 material

The analysis results from Table 15 yield the following correlation between the surface hardness and the peening parameters.

$$\ln(Hv) = 4.7757 - 0.0331 \ln(P) + 0.0155 \ln(S) + 0.3580 \ln(D) - 0.1301 \ln(T)$$

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

Surface hardness (Hv)

$$= 118.59\,(P)^{-0.033}(S)^{0.015}(D)^{0.358}(T)^{-0.13} \quad (1)$$

Table 15 Intercepts and coefficients for surface hardness for AISI 1045

Term	Coefficient	SE	*p*	95% CI of coefficient
Intercept	4.7757	1.6093	0.0128	1.2337 to 8.3177
ln (*P*)	−0.0331	0.1089	0.7665	−0.2728 to 0.2065
ln (*S*)	0.0155	0.1227	0.9019	−0.2545 to 0.2855
ln (*D*)	0.3580	0.3382	0.3125	−0.3863 to 1.1023
ln (*T*)	−0.1301	0.1089	0.2572	−0.3697 to 0.1095

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

Table 16 Intercepts and coefficients for surface hardness for 316L

Term	Coefficient	SE	*p*	95% CI of coefficient
Intercept	8.5477	2.6354	0.0078	2.7472 to 14.3482
ln (*P*)	−0.0263	0.1783	0.8854	−0.4187 to 0.3661
ln (*S*)	0.1603	0.2009	0.4418	−0.2818 to 0.6024
ln (*D*)	−0.4684	0.5538	0.4157	−1.6873 to 0.7505
ln (*T*)	−0.0803	0.1783	0.6610	−0.4727 to 0.3120

P pressure, *S* shot type, *D* nozzle distance, *T* exposure time

5.2 Quantification for 316L material

Similarly, the analysis from the results of Table 16 yield the following correlation between the surface hardness and the peening parameters.

$$\ln(Hv) = 8.55 - 0.0263\ \ln(P) + 0.1603\ \ln(S) - 0.4684\ \ln(D) - 0.0803\ln(T)$$

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

$$\mathit{Surface\ Hardness}\ (Hv) = 5154.88\ (P)^{-0.026}(S)^{0.16}(D)^{-0.47}\ (T)^{-0.08} \tag{2}$$

Since R^2 values for both materials (Tables 17 and 18) are less, Eqs. 1 and 2 give approximate values. However, they would serve as a useful guide for selecting proper values of process parameters for the above materials so as to obtain desired surface hardness of the component.

6 Conclusions

Shot peening is an important process for enhancing surface integrity of components. To keep pace with the competitive market, it is necessary for the industry to enhance productivity of this process. In view of this, an experimental investigation on shot peening of AISI 1045 and 316L materials was conducted using a full factorial experimental technique. Effects of shot peening parameters, viz. pressure (P), shot size (S), exposure time (T), and nozzle distance (D) and their interactions on surface hardness, were studied using ANOVA. In addition, variation of surface hardness in the direction of peening was also studied. It was found that the process parameters that have influence on surface hardness of AISI 1045 in decreasing order of significance are: exposure time, nozzle distance, shot size, and pressure. For 316L material, the order of significance is: nozzle distance, shot size, exposure time, and pressure. Regression models correlating surface hardness with process parameters have also been obtained and are as follows.

For AISI 1045 material:

$$\mathit{Surface\ hardness}\ (Hv) = 118.59\ (P)^{-0.033}(S)^{0.015}(D)^{0.358}(T)^{-0.13}$$

For 316L material:

$$\mathit{Surface\ Hardness}\ (Hv) = 5154.88\ (P)^{-0.026}\ (S)^{0.16}\ (D)^{-0.47}\ (T)^{-0.08}$$

These equations can serve as a useful guide for setting proper values of process parameters so as to obtain desired surface hardness of the component.

Table 17 ANOVA for surface hardness for AISI 1045

Source of variation	SSq	DF	MSq	*F*	*p*
Due to regression	0.061	4	0.015	0.66	0.6298
About regression	0.251	11	0.023		
Total	0.311	15			
R^2	0.19				

Table 18 ANOVA for surface hardness for 316L

Source of variation	SSq	DF	MSq	*F*	*P*
Due to regression	0.096	4	0.024	0.39	0.8087
About regression	0.672	11	0.061		
Total	0.768	15			
R^2	0.13				

Acknowledgement The authors are pleased to acknowledge J.K. Files Pvt. Ltd. Ratnagiri for their cooperation in carrying out microhardness testing. Special thanks are due to Mr. D.D. Langekar (metallurgist) for his help in microhardness tests.

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