



Efficiency Analysis of Shot Peening Parameters on Variations of Hardness, Grain Size and Residual Stress via Taguchi Approach

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Abstract

In the present study, the main purpose is to detect the most key factors of shot peening (SP) process on the microhardness, grain size, and residual stress of AISI 1060 high carbon steel. The specimens were treated using various types of SP process namely conventional shot peening and severe shot peening. Several experiments were performed to study metallurgical and mechanical properties of AISI 1060 steel. Almen intensity and surface coverage from one side and microhardness, grain size, and residual stress from the other side were considered as input and output parameters for the design of experiment methodology, respectively. The $L_{18}(2^1 \text{ and } 3^1)$ mixed level of Taguchi orthogonal array design was used to study all cases. The test results were investigated by signal-to-noise ratio formula. It was identified that the surface coverage is the most key factors for shot peening process considering the affected depth. Also, the effect of this parameter on the microhardness, grain size and residual stress was obtained approximately 68, 89 and 57%, respectively. Eventually, the results obtained from all Taguchi sensitivity analysis indicated that it would be better to adjust the surface coverage factor in comparison with Almen intensity factor in order to create the surface compressive residual stress on the material and consequently to increase the fatigue lifetime of component using shot peening treatment.

Keywords Shot peening · Almen intensity · Surface coverage · Design of experiment · Taguchi approach

1 Introduction

AISI 1060 high carbon steels have the common use areas particularly cam shafts, drive train shafts and axles, crank shafts and velocity joints. Automotive and air-craft applications requires the material for dynamically loaded parts. Surface treatments such as deep rolling [1], with pre-post heat treatment [2], grinding-hardening processes [3] and laser processing [4] have been applied to improve the surface characteristics. Some of the processes might adversely affect the surface due to very high/low temperatures during applications. Therefore room temperature mechanical

surface treatments (shot peening, UNSM and etc.) have the advantages to change the surface characteristics without any distortion interior by high/low temperature applications [5].

Shot peening, which is widely employed in different industries, is a cold working process caused by the impacts of small shots on the component surfaces with controlled parameters [6–8]. Generally, different parameters including air projection pressure, shot diameter, flow rate, and peening duration have to be regarded in use of the air blast shot peening equipment [9, 10]. In the SP process, to avoid too many variables, two parameters of Almen intensity (affected by projection pressure, shot diameter, and flow rate) and surface coverage (affected by peening duration time) are regarded as only major items in control [11–14]. Based on the values of above-mentioned parameters, the severity of applied SP is specified which is usually categorized into two sets of CSP and SSP that employs the surface coverage of 100% and $N \times 100\%$ ($N=2, 3 \dots$), respectively [15, 16]. Although both CSP and SSP processes have beneficial effects on the majority of materials properties, it has been proven that the SSP has superior effects than CSP in mechanical properties and high cycle fatigue life (HCFL) improvements [17–22].

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Studies on the importance of various SP parameters on mechanical and metallurgical properties of metallic materials have been carried out via applying different techniques such as finite element method (FEM), response surface methodology (RSM), multi-criteria decision making (MCDM), and artificial neural networks (ANN).

Jebahi et al. [23] have presented a robust methodology to simulate 3D random shot peening process using coupling model of discrete element method (DEM) and finite element method (FEM). The representative elementary volumes (REVs) have been used to reduce the target component geometry made of SAE 1070 spring steel in finite element simulation and in order to decrease computational costs, DEM has been utilized to model a large number of rigid shots. Eventually, the residual stress distribution has been presented in an A17075-T73 disk specimen which is peened with S230 steel shots and 200% coverage. They showed that the compressive residual stress due to SP process will be disappeared in the depths of less than 0.5 mm. Wang et al. have investigated the grain refinement of AISI 4340 steel induced by SSP process including various surface coverage (200, 650, and 1000%) [24]. The results of this study have shown that for all shot peening cases with consider different impact angles, the grain size will be converged in the depth range of 300–500 microns. On the other hand, the influence of different types of SP processes on the grain size is maximally up to a depth of 500 microns. Murugaratnam et al. [25] have optimized the shot peening parameters (shot diameter, nozzle distance, initial velocity, and mass flow rate) using a couple model of DEM-FEM. Also, normalized residual stress σ_{xx}/σ_0 have been presented in terms of depth for different impact angles (35, 45, 62.5, 67.5, 75, and 90) of shots on the surface material. The results demonstrated that inaction depth of negative residual stress also increases by raising the impact angle so that the minimum (0.54 mm) and maximum (0.9 mm) inaction depth are related to the impact angle of 35 and 90 degrees, respectively. Moreover, the surface roughness generated by shot peening process has been studied experimentally and numerically [26]. Response surface method has been employed to optimize the shot peening parameters [27]. It has been predicted that the variables of “air pressure”, “peening duration x air pressure”,

and “shot diameter x air pressure” are the most significant parameters of Almen intensity. Therefore, the air pressure plays a crucial role in determining Almen intensity. Also, the most effective parameter on surface hardness of the material is also the air pressure which is expressed Almen intensity parameter of the shot peening process. Moreover, a complex decision-making tool has been used to perform shot peening optimization by Unal and Maleki [28]. Fatigue behavior of shot peened mild carbon steels has been studied using axial fatigue testing data and artificial neural networks [29]. The results showed that in the SP process, the effect of surface coverage (69%) on the fatigue life of a group of mild carbon steels (AISI 1045 and 1050) is greater than the Almen intensity with a 31% influence. Regarding the parameters of material properties including ultimate stress, yield stress, and carbon content are the most effective parameters with a 49, 32, and 19% influence, respectively. The technique of ANN has been used to model the CSP and SSP effects on the properties of AISI 1060 steel [30]. In the mentioned study, different quantities such as rate of training, number of layers and various types of hidden and output transfer functions (i.e. linear, logsig, and tansig) have been investigated in order to achieve the best structure for accurate modeling of the SP process. In addition, this technique has been used to model and predict the mechanical and metallurgical properties of 18CrNiMo7-6 steel [31].

Although a wide range of studies are performed in literature, the nature of shot peening process prevents to construct certain boundaries between the parameters of the process against hardness, residual stress and grain size distribution. The outputs are always to be kept under high precised control according to the desired purpose. According to the desired outputs technical inputs (air rpressure, surface coverage, shot size and etc.) have to be optimized for each process and each materials to be applied. Therefore, in the present study, a sensitivity analysis was performed on the effective parameters of SP process which affect hardness, grain size, and residual stress of the surface to the depth of material. Experimental data of shot peened carbon steel AISI 1060 were employed to create the Taguchi method.

Table 1 Chemical composition of AISI 1060 high carbon steel (wt%)

C	Si	S	P	Mn	Ni	Cr	Mo	Fe
0.57–0.65	0.40	0.035	0.035	0.60	0.40	0.40	0.10	Bal.

2 Experiments

2.1 Material and Specimens

AISI 1060 high carbon steel is employed in this study and its chemical composition is presented in Table 1. The specimens were fabricated from a hot-rolled sheet in a rectangular shape with dimensions of 10×20 mm and 6 mm thickness. Specimens were quenched from 850 °C in oil, tempered at 310 °C for 1 h, and then ground by a very soft grinder.

2.2 Shot Peening Treatments

Shot peening treatments were carried out with different conditions. SAE J443 standard was used for determination of Almen intensity [32] and the related effective parameters of accomplished SP treatments are presented in Table 2.

2.3 Microstructural Characterizations

Microstructural characterization was performed by VEGA\\TESCAN-XMU scanning electron microscope (SEM) and field emission scanning electron microscopy (FESEM) using Mira 3-XMU. Specimens were etched by 2% Nital before microscope observations. Also, XRD measurements and high-resolution transmission electron microscope were applied to determine the grain size at the treated surfaces. To apply XRD analysis, X'Pert PRO MPD (PANalytical) X-ray diffractometer system and X'Pert High Score Plus (V. 3) analyzer were used with Cu K α radiation operated at 40 kV and 40 mA, the scanning angle of 30°–150° and irradiated area of 10 mm. To apply HRTEM, specimens were ion polished up to the thickness of about 60 μ m via disc grinding. HRTEM was performed using JEOL JEM 2100 High-Resolution Transmission Electron Microscope operated with 200 kV operation condition. The mean grain size was evaluated from layers within a vertical range of 10 μ m with total counts of 75 measurements.

Table 2 Effective parameters of accomplished SP treatments

Treatment no.	Almen intensity (0.001 mm A)	Surface coverage (%)	SP treatment type
1	17	100	CSP
2	17	700	SSP
3	17	1500	SSP
4	21	100	CSP
5	21	700	SSP
6	21	1500	SSP

2.4 Hardness and Residual Stress Measurements

Hardness measurements were carried out via microhardness tester of Qness GmbH Q10 with a load of 10 gf and duration of 8 s using Vickers indenter on the surface and in depth up to 400 μ m for achievement of the hardness profile. Residual stresses were measured by utilizing Xstress 3000 G2/G2R X-ray Stress Analyzer (radiation Cr K α , irradiated area of 4 mm diameter, diffraction angle (2θ)~156°, and ψ scanned between 45° and –45°). Moreover, the operation of removing layers was done considering the intervals of 20 μ m via electro-polishing in order to determine the residual stresses in the depth of SP treated component.

3 Design of Experiment Based on Taguchi Method

The Taguchi method was employed to determine the effect of different parameters of the SP process (wt%) on the metal-lurgical and mechanical properties of SAE-AISI 1060 steel. Previously in this field, Sun et al. [33] have optimized laser shock peening via finite element method and Taguchi method. Parameters of laser power, pulse width, and laser shot diameter have been used as the input parameters and the surface residual stress has been regarded as an output parameter. Jamaluddin et al. [34] have improved the quality of the shot blasting process by applying Taguchi approach and performing various tests. Pathak and Munjadas [35] have optimized parameters of SP process on the Al 2024 alloy specimens which the effects of shot size, shot velocity, impact angle, and shot distance on the surface residual stress and surface roughness were investigated in their study. Also, the influences of SP parameters (shot diameter, speed, and duration of treatment as time) have been investigated on the surface roughness and tensile strength of Aluminum 6061 as well [36]. Empirical studies have been done on the SP parameters for welded austenitic stainless steel in association with surface hardness and static strength [37]. In addition to the above parameters, the flow rate is also gathered as an effective parameter of the SP process [38]. The effects of SP parameters on the ultimate strength of low carbon steel have been explored by applying tensile tests on v-notched specimens (angle and depth of notch are 45 degrees and 2 mm, respectively) [39].

In this study, two variables with different levels (Almen intensity with two levels and surface coverage with three levels) are used to create the Taguchi method. All measurement were performed in every 60 μ m intervals from the surface to the depth of 420 μ m and Taguchi sensitivity analysis was repeated in every depth. The most influence parameter was specified in every depth separately for microhardness, grain size, and residual stress results. Moreover, the low-effect parameter was determined in each depth. Generally, there are some well-known criteria such as nominal-the-better,

the smaller-the-better, and the larger-the-better ratios of S/N for quantifying of the quality [40–43]. Here, with a view to minimizing the grain size, the smaller-the-better criterion was employed for the calculation of S/N ratios using Eq. (1) [44, 45]:

$$S/N = -10\text{Log} \left[\frac{1}{n} (y_1^2 + y_2^2 + \dots + y_n^2) \right] \quad (1)$$

and with a view to maximizing the microhardness and residual stress, the larger-the-better criterion was employed for the calculation of S/N ratios using Eq. (2):

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

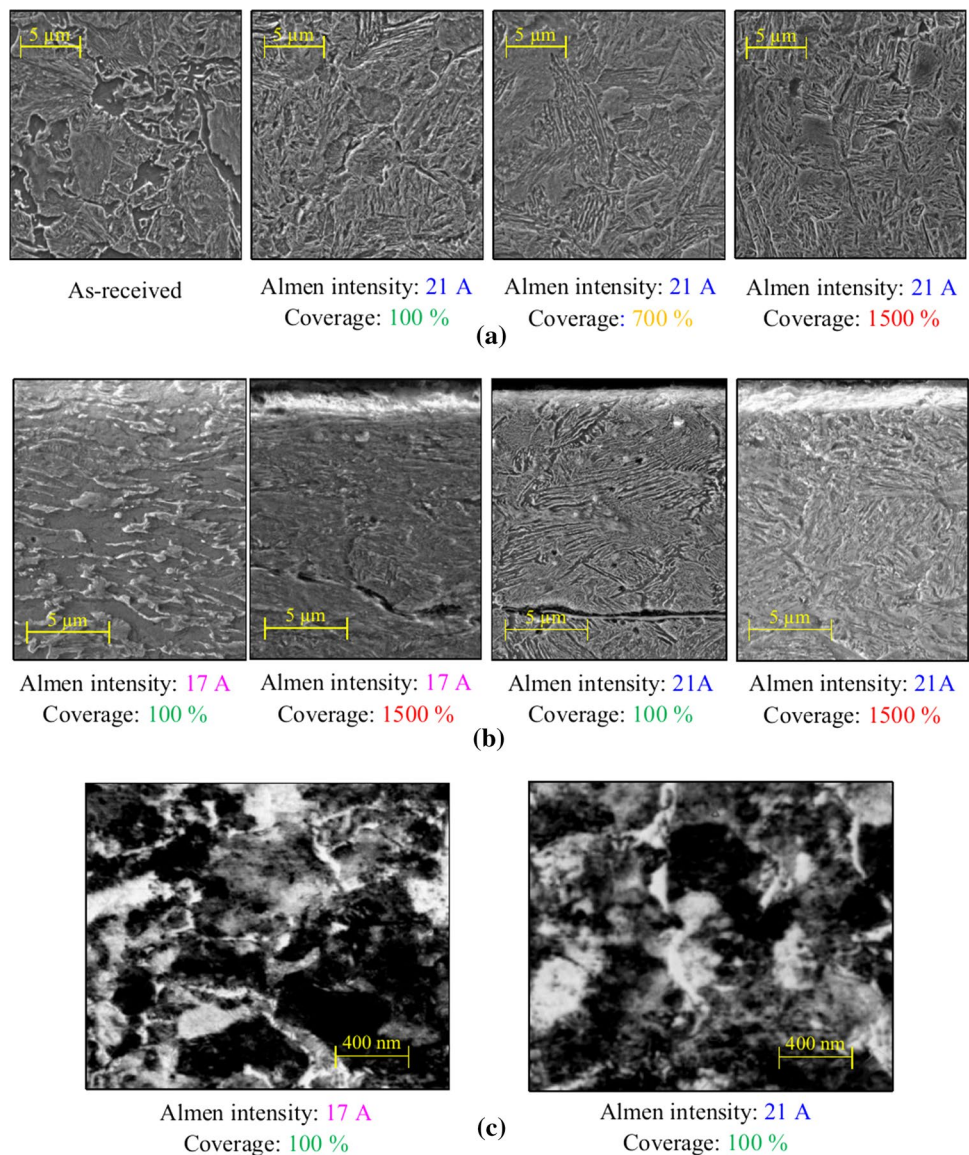
where y_1, y_2, \dots, y_n represent the measured bent angles in the bending process, and each bending condition is repeated for n times and then in each parameter level, the main effects of S/N ratios were analyzed and plotted.

4 Results and Discussion

4.1 Experimental Findings

SEM, FESEM, and HRTEM methods were used for microstructure observation of the treated specimens. In Fig. 1, all images of SEM, FESEM, and HRTEM are presented. Figure 1a shows the comparison of the as-received and treated specimens with Almen intensity of 21A and

Fig. 1 Microstructural observations of the as-received and shot-peened specimens through different methods of **a** SEM, **b** FESEM, and **c** HRTEM



different coverages. It can be seen in Fig. 1b (cross-sectional FESEM images), CSP treatments caused to generate a refined grain layer below the upper surface of the material that patently specified by work-hardened layers. It can be observed that by enhancing the SP process kinetic energy, the grain size is decreased and the surface is become compacted more and more. In the SSP treatments which in this study have 700 and 1500% coverages for every considered intensities including 17 and 21A, distinct layer isolated with sharp boundaries from the underlying plastically deformed layer that demonstrates dense structure layer beneath the surface, as reported by Saitoh et al. [46]. To specify the variations of the grain size in depth, as previously reported by Maleki et al. [19, 20], two different techniques of XRD analysis and TEM observations were used. In the surface of severely treated specimens, XRD measurements (Fig. 2) were applied and after obtaining the values of full width at half maximum (FWHM) and 2-theta for each sample, grain size was calculated by Scherer's equation as follows:

$$d_{XRD} = K \lambda / \beta \cos\theta \quad (3)$$

where d is apparent size of the crystal, λ is the wavelength of the x-radiation (i.e. $\lambda_{Cu-K\alpha} 1.54 \text{ \AA}$), B is the corrected FWHM, θ is the diffraction angle, and K is a constant (its value is close to one; i.e. 0.94). β can be obtained from observed FWHM by convoluting Gaussian profile which models the specimen broadening β_r , as follows:

$$\beta_r^2 = \beta_0^2 - \beta_i^2 \quad (4)$$

where β_0 is observed broadening and β_i is instrumental broadening.

According to the XRD analysis and using Scherer's equation, average sizes of crystallites of the severely

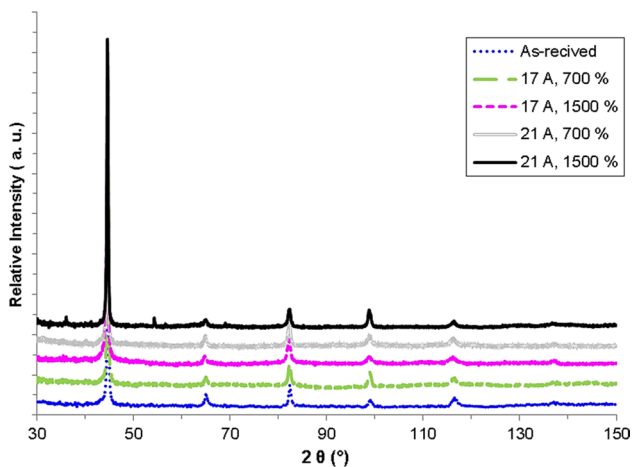


Fig. 2 Intensity distribution of as-received and severely treated specimens

Table 3 FWHM and crystallite sizes of specimens peened with SSP treatments

Shot peening parameters	2 θ ($^{\circ}$)	FWHM ($^{\circ}$)	Crystallite size (nm)
17 A, 700%	44.653	0.117	82
17 A, 1500%	44.534	0.194	48
21 A, 700%	44.601	0.182	52
21 A, 1500%	44.588	0.210	45

shot-peened specimens are determined and presented in Table 3.

The grain size in the specimens treated with CSP processes was determined via HRTEM observations. Figure 1c reveals the HRTEM images of the conventionally treated specimens. According to the all mentioned above and microstructural characterizations, the deformed, unblurred and properous to amorphous transformation layer is created and thickened by higher SP severity. The layer compactness, complexity and thickness bring grain refinement effectivity in the literature studies. The grain size evaluation by crsyallite size investigations presents and supports the assessment of the microstructural approach. According to the applied microstructural characterization through different approaches, several experiments, and also results of XRD measurements, the grain size was achieved in each shot-peened specimens at different depths.

In addition, from the surface to depth of 420 μm in every 60 μm intervals, variations of microhardness and residual stress were determined. The interval range of 0–420 μm was chosen because most of the changes have occurred in the values of mentioned parameters (microhardness, residual stress, and grain size). In this way, variations of these parameters in the shot-peened specimens with different intensities of 17 and 21A and various coverages of 100 and 1500% are shown in Fig. 3 and all detailed results are reported in “Appendix”. It is seen that by enhancing both Almen intensity and coverage values, more grain refinement is accomplished and also the values of hardness and compressive residual stress are increased remarkably.

4.2 Taguchi Analysis

In the present study, Almen intensity with different levels of 17 and 21A and surface coverage with three levels including 100, 700, and 1500% were considered as input variables for Taguchi analysis. The $L_{18}(2^1 \text{ and } 3^1)$ mixed level of Taguchi orthogonal array design was used to create the test algorithm as shown in Table 4. This technique is efficient and costs saving due to the minimum number of experimental specimens in comparison with the full factorial

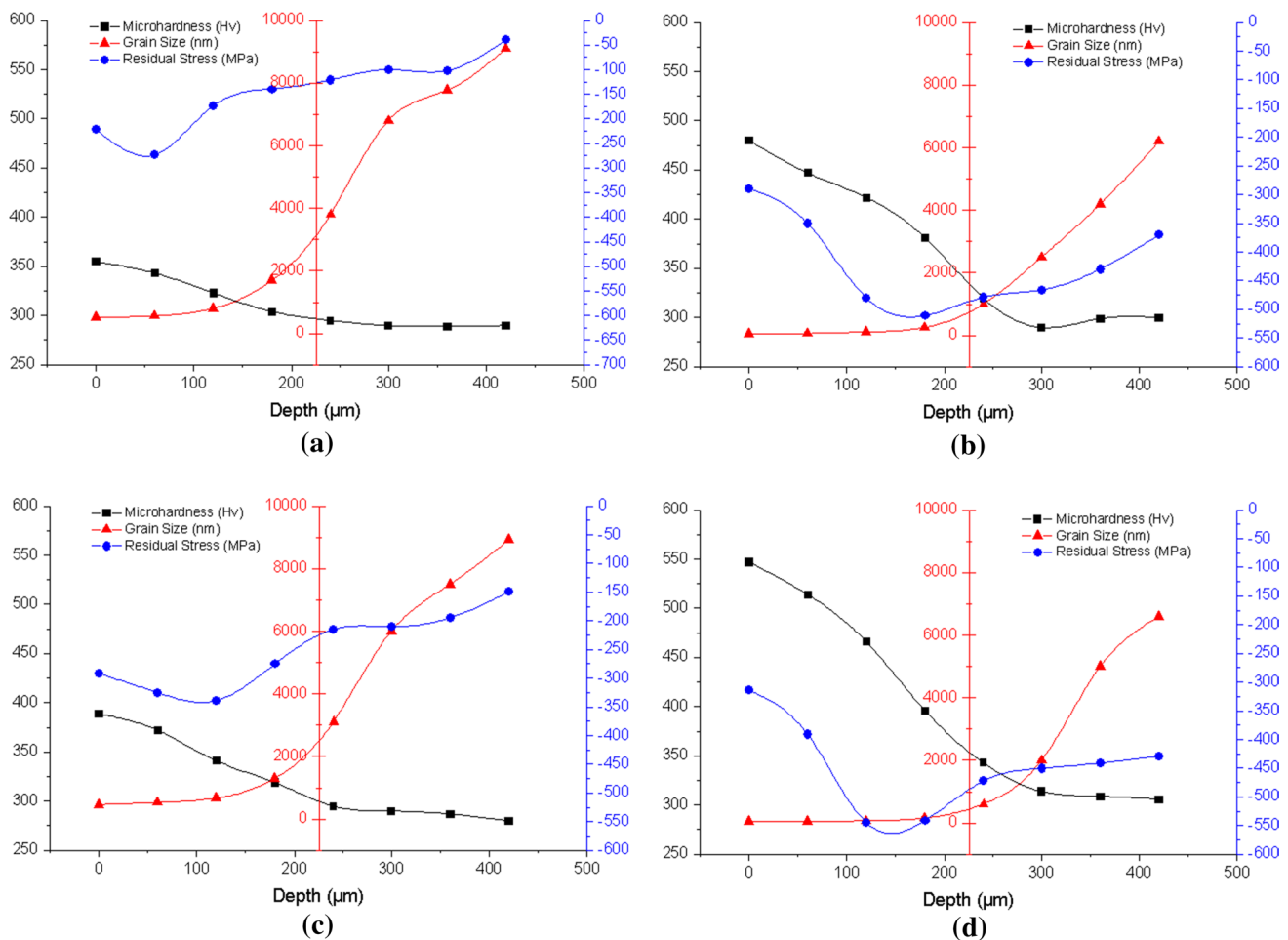


Fig. 3 Variations of microhardness, grain size, and residual stress in depth for the shot-peened specimens with different treatments including **a** Almen intensity of 17 A and coverage of 100%, **b** Almen inten-

sity of 17 A and coverage of 1500%, **c** Almen intensity of 21 A and coverage of 100%, and **d** Almen intensity of 21 A and coverage of 1500%

design method. As shown in “Appendix”, various experiments at the material surface up to depth were performed for different DOE cases to study metallurgical and mechanical properties of high carbon steel including measurement of microhardness, grain size, and residual stress. It is clear that compressive residual stresses induce at the surface layer after various types of SP process; but, in order to perform Taguchi analysis, all parameters should have positive values. Hence, instead of using negative residual stresses, the positive values of compressive residual stress were employed.

Taguchi sensitivity analysis was performed at different depths and the plots of signal-to-noise (S/N) ratios for Almen intensity and surface coverage in all of the considered outputs are presented in Fig. 4. For microhardness,

it is clear that the effect of SP goes to zero by increasing of depth from the surface which is seen in both images of Fig. 4a and the system responses to a certain value, when the measured depth is greater than 420 μm . In the analysis of grain size variations, according to Fig. 4b, all lines related to the parameter of Almen intensity are almost straight. This subject expresses that different levels of Almen intensity factor have a very low effect on the grain size of shot peened samples. Also, the same result can be extended to the surface coverage factor for measured depths of more than 300 μm . For residual stress analysis, according to Fig. 4c, when the measured depth is lower than 60 micrometers, different levels of surface coverage factor have not affected the compressive residual stress. On the other hand, the residual stress

Table 4 The $L_{18}(2^1 \text{ and } 3^1)$ mixed level of Taguchi orthogonal array design

Experiment no.	Factor	
	A	B
1	1	1
2	1	1
3	1	1
4	1	2
5	1	2
6	1	2
7	1	3
8	1	3
9	1	3
10	2	1
11	2	1
12	2	1
13	2	2
14	2	2
15	2	2
16	2	3
17	2	3
18	2	3

value on the surface and in the depth near the surface only depends on the value of Almen intensity.

The creation of compressive residual stress on the surface of the materials is the main reason for applying SP in various industries besides the other structural integrities (such as mechanical properties improvements). The fatigue life of materials can be increased by raising the compressive residual stress at the component surfaces [7, 29, 47–49]. Hence, Taguchi sensitivity analysis was performed for different shot peening parameters to determine the most effective parameter on the value of surface

compressive residual stress. In Fig. 5a–c, efficiency percentage of both Almen intensity and surface coverage are presented in every depth. Eventually, it can be concluded that the surface coverage factor of shot peening process has the most influences on the microhardness and grain size at different depths. However, residual stress in different depths has different behavior so that on the top surface to the depth of less than 120 μm , the parameter of Almen intensity is more effective and in the range of 120–420 μm depths, coverage factor has more importance. Also, the overall effects of intensity and coverage in the whole considered depths from 0 to 420 μm are determined and illustrated in Fig. 5d that shows coverage has more efficiency than intensity.

Based on the investigation of whole obtained experimental results and Taguchi analysis, schematic diagram of effects of different applied SP treatments on AISI 1060 on grain refinements as well as the influences of Almen intensity and coverage on the material properties such as hardness, grain size, and residual stress at different depths is illustrated in Fig. 6. The colored boxes in the table presented in Fig. 6 show the more efficient parameter in each considered depth on the output parameters of microhardness, grain size, and residual stress.

5 Conclusion

In the present study, the influences of shot peening parameters on properties of high carbon steel were investigated by using the Taguchi method. In order to develop a Taguchi approach, Almen intensity and surface coverage were considered as inputs and the microhardness, grain size, and

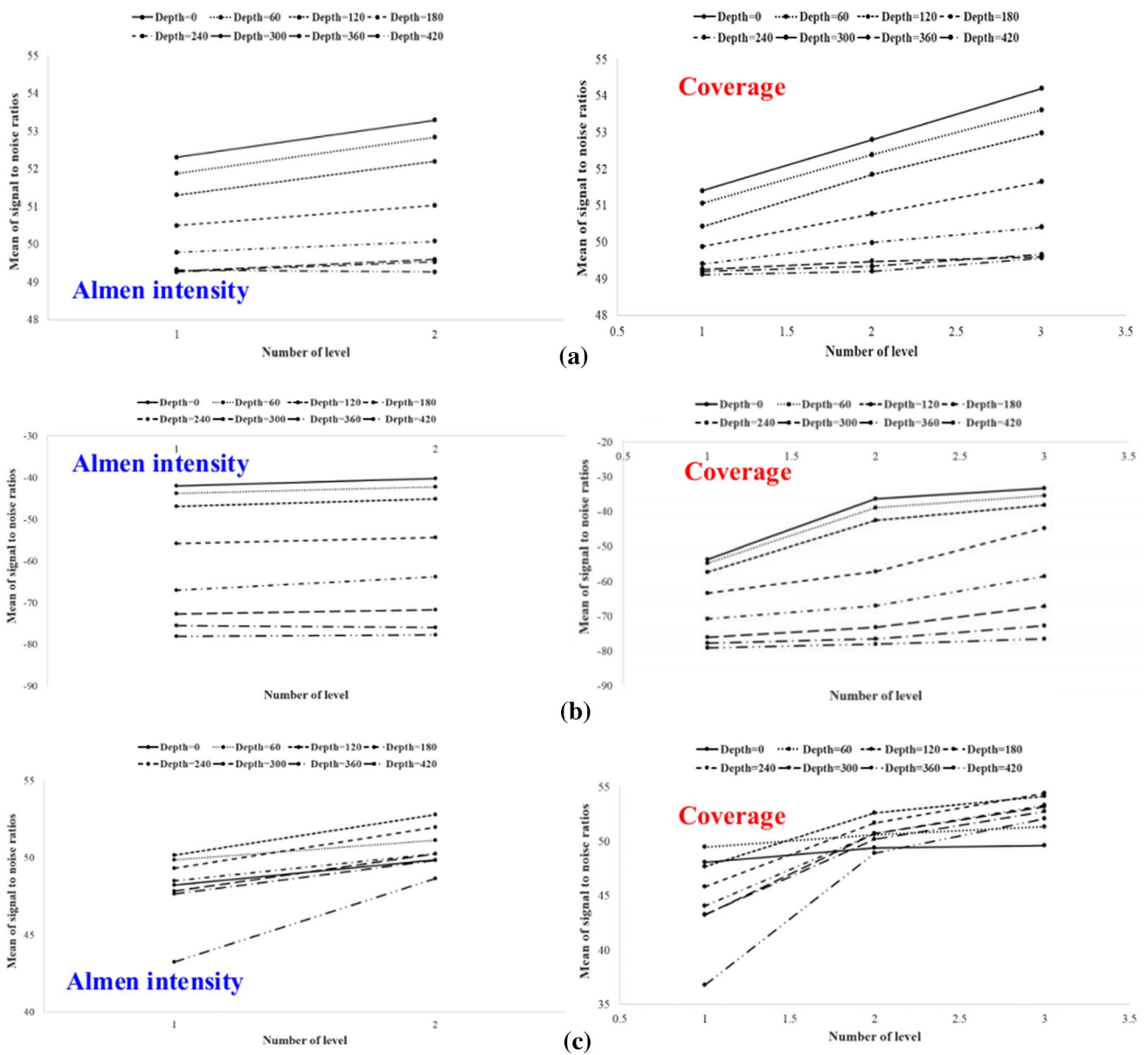


Fig. 4 Effects of Almen intensity and surface coverage on the **a** microhardness, **b** grain size, and **c** residual stress of shot peened AISI 1060 steel subjected to different treatments

residual stress were gathered as output parameters. Afterward, various types of tests were performed for several cases of shot peened AISI 1060 steel. Achieved results show that:

- Surface coverage is the most key factors for shot peening process. And its weight values are 68, 89 and 57% for microhardness, grain size, and residual stress, respectively.
- Shot peening influence goes to zero by depth increasing more than 420 micrometers in AISI 1060 high carbon steel.
- Different levels of Almen intensity factor will not effect on the grain size of shot peened samples. The same result can be extended to the surface coverage factor for measured depths of more than 300 micrometers.
- Almen intensity factor is more efficient to create the compressive residual stress on the top surface layer.

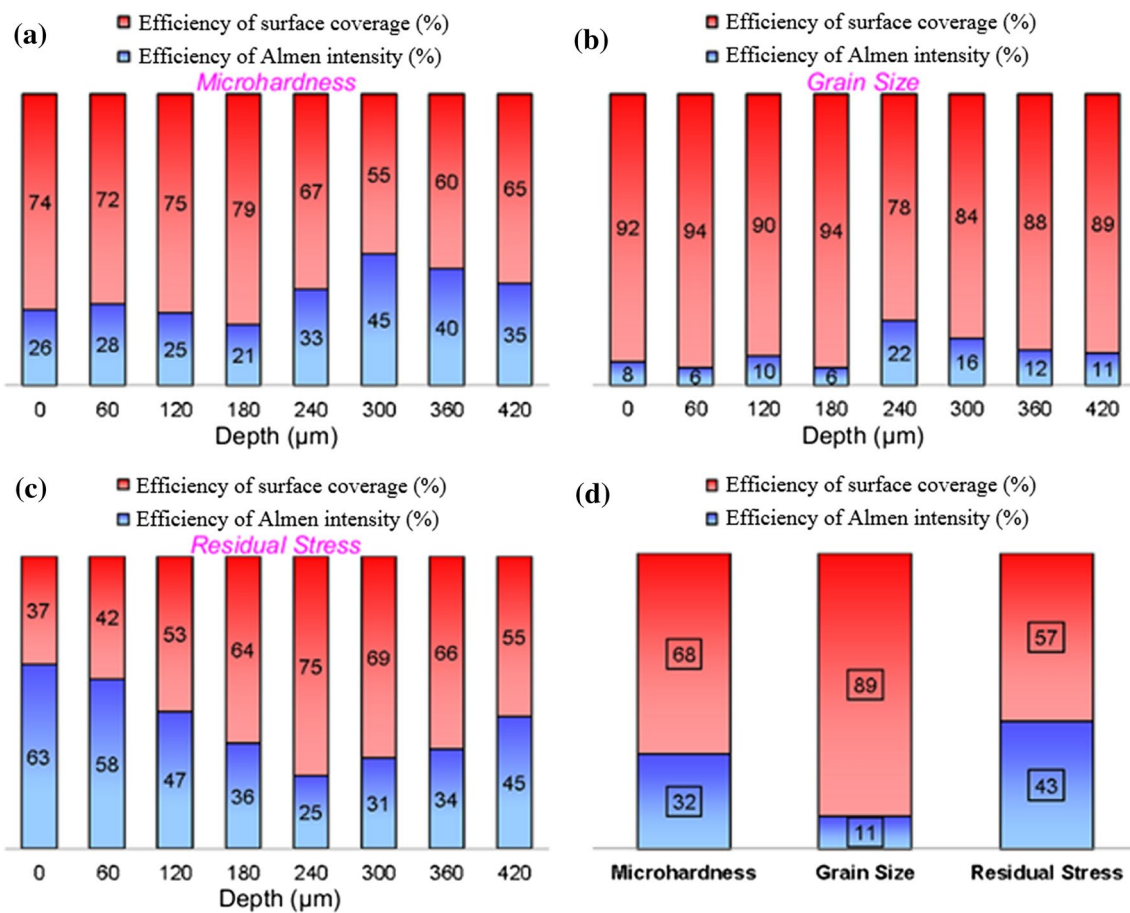


Fig. 5 Efficiency analysis of Almen intensity and coverage from surface to depth on different responses of **a** microhardness, **b** grain size, **c** residual stress, and **d** overall effects of intensity and coverage in the whole considered depth from 0 and 420 μm

Compliance with Ethical Standards

Conflict of interest The authors state that they have no conflicts of interests.

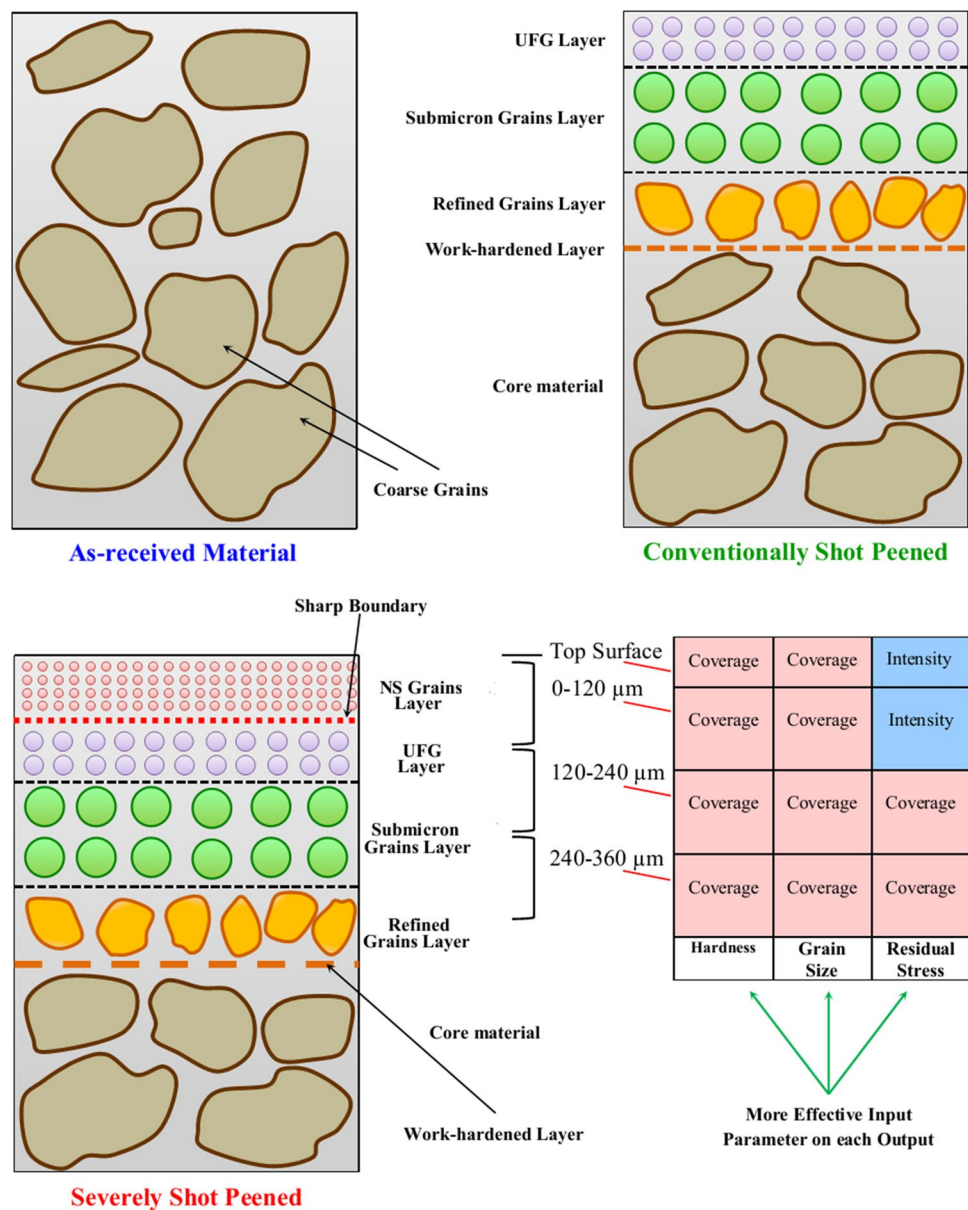
Appendix

See Table 5.

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Fig. 6 Schematic diagram of effects of different applied SP treatments on AISI 1060 on grain refinements as well as the influences of Almen intensity and coverage on the material properties such as hardness, grain size, and residual stress at different depths



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Table 5 Values of considered inputs and outputs based on the design of experiments (Taguchi algorithm) at different depths

Experiment no.	Depth (μm)	Input parameters		Output		
		Almen intensity (0.01 mm A)	Surface coverage (%)	Microhardness (Hv)	Grain size (nm)	Compressive residual stress (MPa)
1	0	17	100	355	515	221
2	0	17	700	411	82	267
3	0	17	1500	480	48	291
4	0	21	100	389	460	292
5	0	21	700	463	52	327
6	0	21	1500	547	45	314
7	60	17	100	343	560	273
8	60	17	700	394	100	314
9	60	17	1500	447	66	350
10	60	21	100	372	532	325
11	60	21	700	440	77	369
12	60	21	1500	514	53	391
13	120	17	100	323	800	173
14	120	17	700	363	151	404
15	120	17	1500	422	90	480
16	120	21	100	341	670	339
17	120	21	700	421	121	452
18	120	21	1500	470	72	545
19	180	17	100	304	1700	139
20	180	17	700	323	750	352
21	180	17	1500	381	189	511
22	180	21	100	319	1300	275
23	180	21	700	369	700	420
24	180	21	1500	383	160	541
25	240	17	100	295	3800	121
26	240	17	700	311	2500	324
27	240	17	1500	320	1200	479
28	240	21	100	295	3100	210
29	240	21	700	320	2000	366
30	240	21	1500	343	600	450
31	300	17	100	290	6800	100
32	300	17	700	294	4700	322
33	300	17	1500	290	2500	466
34	300	21	100	290	6000	210
35	300	21	700	301	4500	366
36	300	21	1500	314	2100	450
37	360	17	100	289	7770	109
38	360	17	700	283	7000	300
39	360	17	1500	299	3800	430
40	360	21	100	287	7510	195
41	360	21	700	303	6500	348
42	360	21	1500	309	5000	441
43	420	17	100	290	9100	32
44	420	17	700	287	8100	258
45	420	17	1500	300	7000	370
46	420	21	100	281	8950	149
47	420	21	700	290	7800	304
48	420	21	1500	301	6600	439

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