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Research Article

Statistical Modeling and Optimization of Variables Affecting Surface Hardness and Corrosion Resistance of 316L Stainless Steel in Ultrasonic Shot Peening Process Using Desirability Approach

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ABSTRACT

Ultrasonic shot peening (USP) has been introduced as a novel method for enhancing the mechanical properties of materials. In this process, spherical shots with certain material, diameter, and quantity are energized with ultrasonic vibrations. These shots impact the surface of the workpiece randomly, creating a layer of compressive residual stresses. This study involved treating cylindrical samples of 316L stainless steel with USP, using various combinations of input parameters (ultrasonic power and peening duration) based on the full factorial design (FFD). Subsequently, the surface hardness and corrosion resistance of the samples were evaluated according to standard procedures. The analysis of variance (ANOVA) results indicated that ultrasonic power significantly affects surface hardness, while both peening duration and ultrasonic power were found to significantly affect corrosion resistance. Furthermore, the coefficient of variation for the models of surface hardness and corrosion resistance was 72.78% and 91.61%, respectively. Given the high signal-to-noise ratios, the regression models are suitable for predicting these response parameters (surface hardness and corrosion resistance). Finally, the optimal combination of the USP input parameters was determined using the desirability approach. The desirability function values, aimed at maximizing surface hardness and corrosion resistance of the steel samples, were 80.2% and 89.3%, respectively.

1. Introduction

Shot peening is a widely used surface treatment process that involves bombarding the workpiece surface with spherical shots of specific material, diameter, and quantity to enhance its mechanical properties [1]. This technique is commonly applied to components such as springs, gears, shafts, axles, turbine blades, and welded joints [2].

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Ultrasonic shot peening (USP) is a new surface treatment process. In USP, shots of specific size and material are energized by a vibrating body operating at ultrasonic frequencies (18-20 kHz). This vibration induces random motions to the shots, which then impact the workpiece surface. The impacts create dimples on the surface and generate distributed compressive loads. Beneath these dimples, the material resists plastic deformation, leading to the formation of compressive residual stress (CRS) and strain-hardening of the material [3].

Key parameters in USP include shot diameter and material, vibration amplitude, peening duration, and peening distance. Due to the effect of these parameters on the mechanical and metallurgical properties of materials, a substantial amount of research has been conducted to explore their effects. Some of these studies are summarized below.

Tao et al. [4] investigated surface nanocrystallization in pure iron using the USP process. The results showed that the USP implementation led to the formation of a nanostructured layer on the iron surface, with an average grain size of approximately 10 nm. In this study, samples were subjected to USP with steel shots of 3 mm in diameter for peening durations of 50, 150, 450, and 1250 seconds. As the peening duration increased, the average grain size also increased, which might be due to the temperature rise. Additionally, with longer peening times, the thickness of the nanostructured layer increased. Pandey et al. [5] studied the effect of the USP process on the fatigue behavior of 7075 aluminum alloy. They found that after applying the USP process for durations of 30, 60, 180, and 300 seconds, nanostructures with average grain sizes of 20, 20, 18, and 16 nm, respectively, were formed on the surface of the specimens. Additionally, the surface hardness of the material before the process was 155 Vickers, which increased to 177 Vickers after 300 seconds of processing. Thus, with an increase in the peening duration, the surface hardness also increased.

Mahobia et al. [6] investigated the nanocrystallization of a nickel-free high nitrogen austenitic stainless steel using the USP process. They performed the USP on the specimens for durations of 2 and 8 minutes at a frequency of 20 kHz and a vibration amplitude of 80 micrometers, using steel shots with diameters of 2 and 3 mm. The results indicated that increasing the shot diameter and peening duration led to finer grains, higher surface hardness, and a thicker work-hardened layer. Dong et al. [7] studied the effect of USP on the wear resistance of the M50 bearing steel. The peening operation was performed using tungsten carbide shots with a diameter of 4 mm for durations of 1, 5, and 10 minutes. They found that the wear rate of the shot-peened samples decreased by 50.4% compared to the original sample.

Kumar et al. [8] studied the effect of USP on the microstructure, hardness, and corrosion resistance of nitrogen-stabilized stainless steel without nickel. The samples were peened at a frequency of 20 kHz and an amplitude of 80 micrometers. After the process, a nanostructured layer was formed on the surface of the material. Additionally, the surface hardness of the material increased by 42% with the use of 3 mm shots and a peening duration of 120 seconds. On the other hand, an increase in peening duration led to a decrease in the corrosion resistance of the samples due to severe surface damage. Agrawal et al. [9] investigated the effect of peening duration on the microstructure and corrosion behavior of pure titanium. The samples were shot peened with 3 mm steel shots at a frequency of 20 kHz and an amplitude of 80 micrometers for durations of 30, 60, 90, and 120 seconds. The results indicated that the peening for 60 to 90 seconds improved the corrosion resistance of the material. However, increasing the peening duration beyond 90 seconds led to a decrease in corrosion resistance.

Zhang et al. [10] studied the effect of USP on the microstructure and corrosion resistance of Ti-6Al-4V alloy produced by selective laser melting. The peening process was carried out using zirconia shots with a diameter of 2.5 mm for durations of 480, 960, and 1920 seconds. The results showed that the USP increased surface hardness, with greater hardness achieved at longer peening durations. Additionally, optimal adjustment of process parameters could enhance corrosion potential, reduce corrosion current density, and improve corrosion resistance. Han et al. [11] investigated the effect of the USP process and subsequent polishing on the surface roughness and corrosion behavior of AZ80M magnesium alloy. The samples were subjected to USP with tungsten carbide shots of 3 mm in diameter, at a distance of 15 mm, with an amplitude of 50 micrometers, for 4 minutes. The USP increased the average surface roughness parameter (R_a) from 0.045 micrometers to 1.165 micrometers. On the other hand, after polishing the shot-peened samples, the average surface roughness parameter (R_a) decreased to 0.043 micrometers. Additionally, the USP and the resulting increase in surface roughness reduced corrosion resistance. However, corrosion resistance significantly improved with the application of polishing after the USP process.

A review of past research shows that the USP process improves the metallurgical and mechanical properties of the workpiece. The creation of CRS and the increase in surface hardness are among the significant benefits of the USP process. On the other hand, the corrosion resistance of the workpiece is influenced by the parameters of the USP process. Therefore, developing regression models and finding the optimal combination of input variables for the USP to predict and maximize surface hardness and corrosion resistance is essential. This study focuses on the statistical analysis and optimization of the variables affecting surface hardness and corrosion resistance of the 316L stainless steel samples.

2. Materials and Methods

316L stainless steel is widely used in the automotive, marine, aerospace, and medical industries due to its high strength and corrosion resistance [12]. In this study, 316L stainless steel samples were subjected to USP. The chemical composition of this grade of steel are presented in Table 1. The physical and mechanical properties of the 316L stainless steel are presented in Table 2. The test samples were prepared in the form of cylinders 20 mm in diameter and 10 mm in thickness, as depicted in Fig. 1.

The Iran-made USP setup was used to perform the surface treatment. In the USP setup, the ultrasonic generator produces electrical signals with a 20 kHz vibration frequency, which are then converted into low-amplitude mechanical vibrations by the transducer. The vibration amplitude is then boosted by the amplifier and transmitted through the vibrating body (horn). As a result of the mechanical vibrations of the horn, the shots are energized in the peening chamber and impact the workpiece surface multiple times.

In this study, 2 mm diameter spherical shots of AISI 52100 steel were employed as the peening media (Table 3). The distance between the front of the horn and the workpiece surface was set to 30 mm. The ultrasonic power and peening duration were selected as variable parameters, each having a lower and upper level, as shown in Fig. 2. For the design of experiments, the full factorial design was used, as outlined in Table 4 [14]. Subsequently, the steel samples were subjected to USP process (Fig. 3).

Table 1. Chemical composition of 316L stainless steel [13]

Element	Composition (wt.%)
Iron (Fe)	Balance
Chromium (Cr)	16.0–18.0
Nickel (Ni)	10.0–14.0
Molybdenum (Mo)	2.0–3.0
Manganese (Mn)	≤ 2.0
Silicon (Si)	≤ 1.0
Carbon (C)	≤ 0.03
Phosphorus (P)	≤ 0.045
Sulfur (S)	≤ 0.03
Nitrogen (N)	≤ 0.10

Table 2. Physical and mechanical properties of 316L stainless steel [12]

Density (g/cm^3)	Poisson's ratio	Young modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)
7.99	0.25	193	290	558

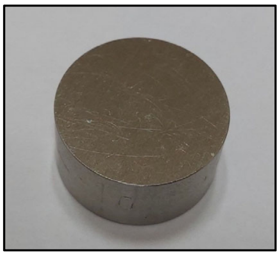

Fig. 1. The original 316L cylindrical specimen (untreated sample).

Table 3. Physical and mechanical properties of AISI 52100 steel [15]

Property	Value
Density	7.81 g/cm³
Young's modulus	210 GPa
Yield strength	1200-1500 MPa
Tensile strength	1800-2200 MPa

Table 4. Design of experiments

Sample no.	Input variables		Response parameters	
	Power (P)	Time (T)	Surface hardness	Corrosion resistance (R_P)
	%	s	HRC	Ohm
1	40	45	17.7	62970
2	40	195	16.8	17710
3	100	45	18.83	18630
4	100	195	22.2	229.9
Untreated sample	-	-	15.6	178500

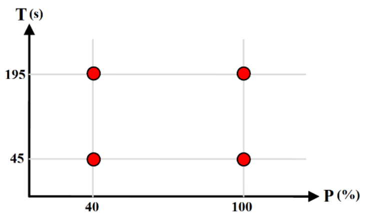

Fig. 2. Variation levels of USP process parameters.

Fig. 3. The shot-peened sample (no. 4).

Surface images of steel samples before and after the application of the USP process were captured using a Dewinter optical microscope with 93X magnification. The surface hardness of the specimens was measured using a Koopa universal hardness tester. The minor load, major load, and dwell time for the hardness test were set to 10 kg, 150 kg, and 3 seconds, respectively. Surface hardness was measured at three different points on each specimen, and the average of the obtained hardness values was recorded as the hardness number.

The corrosion test was conducted on the steel samples using potentiostat/galvanostat equipment (electrochemical workstation). Platinum and calomel electrodes served as the counter and reference electrodes, respectively, while the steel samples were used as the working electrodes in the electrochemical cells. A 3.5 wt.% NaCl solution was employed as the electrolyte. By controlling the voltage between the working and reference electrodes, the electric current passing through the counter electrode was measured (Fig. 4).

The corrosion behavior of the steel samples was analyzed using IVIUM software [16] with a scan rate of 1 millivolt per second.

The data obtained in this study were analyzed using Design-Expert software [17] based on analysis of variance (ANOVA) [18]. Additionally, regression analysis was employed to establish a mathematical function relating the response parameter to the factors affecting the USP process [19]. The confidence level (α) was set to 0.05.

3. Results and Discussion

As shown in Fig. 5, the lines on the surface of the untreated sample are a result of the grinding process. In contrast, with an increase in ultrasonic power, both the quantity of dimples and the resulting surface coverage significantly increased in samples 3 and 4.

3.1. Surface hardness

It should be noted that the surface hardness of the untreated specimen was determined to be 15.6 HRC. This indicates that the surface hardness of all specimens increased following the application of the USP process (Table 4).

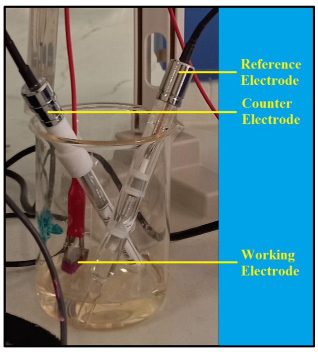

Fig. 4. Electrochemical cell for the corrosion test.

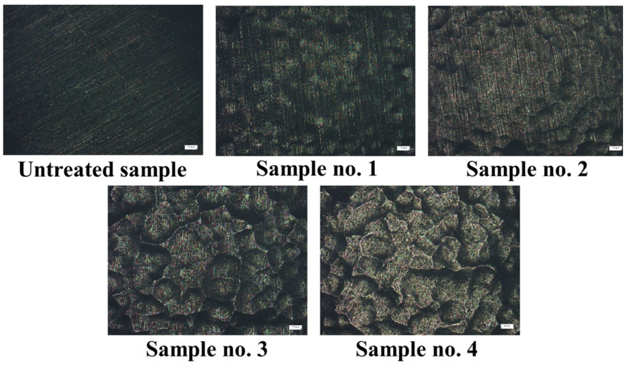

Fig. 5. Surface images of the test samples with 93X magnification.

For example, with increases in both ultrasonic power and peening duration (sample no. 4), the surface hardness increased by 42.3% compared to the untreated sample. Table 5 presents the results of the ANOVA for the surface hardness of the test samples.

The significance of a term is determined by its corresponding P-value: if $P \leq \alpha$, the term is considered significant; otherwise, it is deemed insignificant. A lower P-value indicates a higher significance of the factor in the model. Consequently, ultrasonic power was identified as the significant factor affecting the surface hardness.

The coefficient of variation for the regression model was found to be 72.78%. Additionally, the adequacy of precision, which indicates the signal-to-noise ratio, was obtained as 5.442, confirming the model's suitability for navigating the design space. The regression model, in coded form, was extracted for predicting surface hardness according to the following equation:

$$\text{Hardness} = 18.88 + 1.63P + 0.6175T \quad (1)$$

The interactive effect of the input parameters on surface hardness is shown in Fig. 6. As can be seen, an increase in ultrasonic power and peening duration leads to an increase in the surface hardness of the samples.

3.2. Corrosion resistance

Polarization diagrams (potential vs. current density) were obtained. Consequently, the corrosion resistance and corrosion rate of the steel samples were measured and recorded, as detailed in Table 6.

According to Table 6, the application of the USP process results in a reduction in corrosion resistance and an increase in the corrosion rate. Additionally, increases in both ultrasonic power and peening duration lead to reduced corrosion resistance. To enhance corrosion resistance while keeping the ultrasonic power constant, the peening duration should be decreased. Table 7 presents the ANOVA results for corrosion resistance.

According to the P-values, both peening duration and ultrasonic power were identified as significant factors affecting corrosion resistance. Notably, peening duration has a more substantial effect on corrosion resistance.

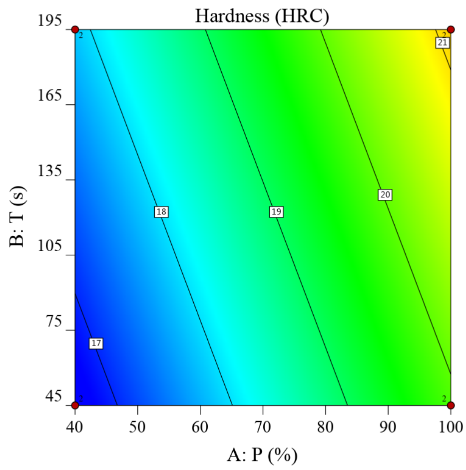

Fig. 6. The interactive effect of the input parameters on the surface hardness.

Table 5. ANOVA results for the surface hardness

Source	Sum of squares	df	Mean square	F-value	P-value
Model	24.37	2	12.19	6.68	0.0387
A-P	21.32	1	21.32	11.69	0.0188
B-T	3.05	1	3.05	1.67	0.2524

Table 6. Corrosion resistance and corrosion rate of the steel samples

Sample no.	Corrosion resistance (ohm)	Corrosion rate (mm/year)
1	62970	0.0003744
2	17710	0.001858
3	18630	0.001637
4	229.9	0.03141
Untreated sample	178500	0.0001173

Table 7. ANOVA results for the corrosion resistance

Source	Sum of squares	df	Mean square	F-value	P-value
Model	3.937	2	1.969	27.297	0.0020
A-P	1.911	1	1.911	26.49	0.0036
B-T	2.026	1	2.026	28.09	0.0032

The coefficient of variation for the model was determined to be 91.61%. Additionally, the adequacy of precision, which indicates the signal-to-noise ratio, was obtained as 12.062, confirming the model's suitability for navigating the design space. The regression model, in coded form, was extracted for predicting corrosion resistance according to the following equation:

$$\text{Corrosion resistance } (R_P) = 24884.98 - 15455.03P - 15915.03T \quad (2)$$

The interactive effect of the input parameters on corrosion resistance is shown in Fig. 7. As can be observed, a simultaneous increase in ultrasonic power and peening duration results in a decrease in corrosion resistance.

4. Optimization and Verification

In this study, the desirability method was used to optimize the USP process parameters [20, 21]. Since the goal of the desirability function is to maximize both surface hardness and corrosion resistance of the steel samples, desirability is defined as follows:

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{U-L}\right)^r & L \le y \le U \\ 1 & y > U \end{cases} \quad (3)$$

In this equation, the parameters L and U represent the lower and upper limits of the response y, respectively. The weight value (r) was considered equal to 1.

4.1. Surface hardness

Table 8 shows the optimal combination of input parameters to achieve maximum surface hardness. As can be seen, the optimal values for ultrasonic power and peening duration were determined to be 100% and 195 seconds, respectively. The value of the desirability function was 80.2%. Comparing the results of the optimization with the hardness measurements for sample no. 4 shows a 5.05% difference in surface hardness, indicating the accuracy of the proposed model for predicting the response parameter.

Table 8. Results of surface hardness optimization

P (%)	T (s)	Hardness (HRC)	Desirability
100	195	21.133	0.802

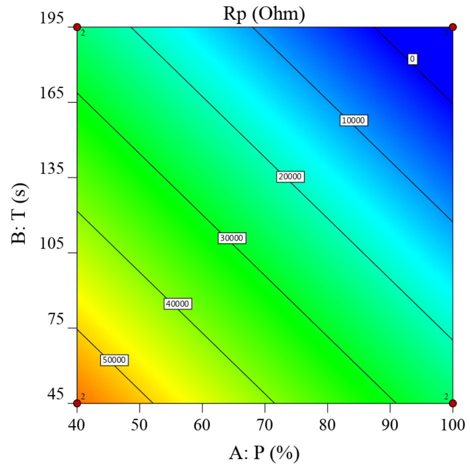

Fig. 7. The interactive effect of the input parameters on the corrosion resistance.

4.2. Corrosion resistance

Table 9 shows the optimal combination of input parameters to achieve maximum corrosion resistance. As seen in Fig. 8, the optimal values for ultrasonic power and peening duration were determined to be 40% and 45 seconds, respectively. The value of the desirability function was 89.3%.

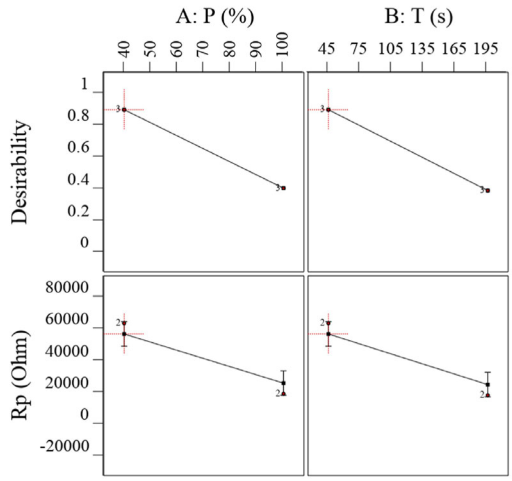

Fig. 8. The optimal combination of input variables to achieve the maximum corrosion resistance with the highest value of desirability.

Table 9. Results of corrosion resistance optimization

P (%)	T (s)	Corrosion resistance (ohm)	Desirability
40	45	56255.025	0.893

Comparing the results of the optimization with the corrosion test results for sample no. 1 shows an 11.94% difference in corrosion resistance.

The study found that surface hardness increased significantly after USP, with the highest hardness achieved at 100% ultrasonic power and 195 seconds of peening duration. This increase in hardness can be attributed to the following microstructural changes induced by USP:

- USP involves the repeated impact of spherical shots on the surface, which induces plastic deformation in the surface layer. This deformation leads to the formation of dislocations and strain hardening, which increases the material's resistance to further deformation and thus increases hardness.
- The higher the ultrasonic power and peening duration, the greater the plastic deformation and strain hardening, resulting in higher surface hardness. Kumar et al. [8] observed a 42% increase in surface hardness in nitrogen-stabilized stainless steel after USP, attributing it to grain refinement and strain hardening.
- USP can cause grain refinement in the surface layer, leading to the formation of a nanocrystalline structure. Smaller grains increase the strength of the material according to the Hall-Petch relationship, which states that yield strength increases with decreasing grain size. Zhang et al. [10] reported that USP increased the surface hardness of Ti-6Al-4V alloy due to the formation of a nanostructured surface layer. Studies by Tao et al. [4] and Pandey et al. [5] have shown that USP leads to the formation of nanostructured layers with grain sizes as small as 10–20 nm, significantly increasing surface hardness.
- USP introduces compressive residual stresses (CRS) in the surface layer, which inhibit crack initiation and propagation. While CRS primarily improves fatigue resistance, it also contributes to increased surface hardness by stabilizing the deformed microstructure.

The study found that corrosion resistance decreased after USP, particularly at higher ultrasonic power and longer peening durations. This reduction in corrosion resistance can be explained by the following factors:

- USP increases surface roughness due to the formation of dimples and micro-craters from the impact of shots. A rougher surface provides more sites for corrosion initiation, such as pits and crevices, which can accelerate corrosion. Han et al. [11] observed that USP increased the surface roughness of AZ80M magnesium alloy, leading to reduced corrosion resistance. However, polishing the peened surface restored corrosion resistance by reducing roughness.
- The repeated impacts during USP can cause micro-cracks and surface defects, which act as stress concentrators and facilitate corrosion. These defects can disrupt the passive oxide layer that protects stainless steel from corrosion. Agrawal et al. [9] found that excessive peening duration (beyond 90 seconds) led to severe surface damage and reduced corrosion resistance in pure titanium.
- While compressive residual stresses generally improve fatigue resistance, they can also increase the susceptibility to stress corrosion cracking (SCC) in certain environments. The high residual stresses induced by USP may contribute to reduced corrosion resistance in aggressive environments.
- Kumar et al. [8] reported that increasing peening duration led to a decrease in corrosion resistance due to severe surface damage. Zhang et al. [10] found that while USP improved surface hardness, it also increased surface roughness, which negatively affected corrosion resistance in Ti-6Al-4V alloy.

5. Conclusions

In this study, ultrasonic shot peening (USP) was applied to 316L stainless steel specimens using the full factorial design and specific combinations of ultrasonic power and peening duration. The surface hardness and corrosion resistance of the samples were measured and evaluated as response parameters. The key findings of this study are:

- A simultaneous increase in ultrasonic power and peening duration results in a 42.3% increase in the surface hardness of the steel samples compared to the untreated sample.
- The implementation of the USP process leads to a reduction in corrosion resistance and an increase in

the corrosion rate of the steel samples. Additionally, to improve corrosion resistance while maintaining constant ultrasonic power, the peening duration should be reduced.

- The results of the ANOVA showed that ultrasonic power has a significant effect on surface hardness. Additionally, both peening duration and ultrasonic power were identified as significant factors affecting corrosion resistance.
- The coefficient of variation for the regression models of surface hardness and corrosion resistance was found to be 72.78% and 91.61%, respectively, indicating the adequacy and suitability of the models.
- The signal-to-noise ratios for the regression models of surface hardness and corrosion resistance were 5.442 and 12.062, respectively, confirming the models' suitability for navigation in design space.
- The optimal values for ultrasonic power and peening duration to achieve the maximum surface hardness and corrosion resistance of the steel samples were determined to be associated with desirability values of 0.802 and 0.893, respectively.

Conflict of interest

The authors state that they do not have any financial conflicts of interest or personal relationships that may have affected their work.

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Data availability

The authors state that the data supporting the results of this research are available in the paper. Also, data sets created during the current study are available from the corresponding author upon reasonable request.

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