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Taguchi analysis of shot peening parameters for surface hardness, wear resistance, roughness, and residual stress in Ti-6Al-4V alloy

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Abstract

Shot peening is a method that improves the mechanical properties of the surface due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface. In this study, the effect of shot peening parameters such as shot diameter, shot velocity, impinging angle, and time duration on residual stress and mechanical properties of Ti-6Al-4V surface was investigated using experimental tests, Taguchi test design method (L9 array), and signal-to-noise analysis. The results showed a 53 and 87 % increase in hardness of specimens with the minimum and maximum hardness and a 27 and 57 % increase in wear resistance of these specimens, respectively, compared to raw specimens, due to refinement and compression of the grains on the surface titanium alloy. Also, the shot impinging angle was a key factor in the shot peening process and affected 59, 64, and 67 % of residual stress, wear resistance, and surface hardness, respectively.

Key words: titanium alloy, shot peening, Taguchi method, microstructures, wear resistance, compressive residual stress

1. Introduction

Shot peening is one of the methods used to improve the mechanical properties of metal alloy surfaces. In this method, the metal surface is affected by successive impacts of shots and severe plastic deformation on the surface during the process, which causes the creation of compressive residual stress and the formation of a nanostructured surface layer, the increase in strength, hardness, and fatigue life of the surface after the process [1-5]. Titanium alloys are mainly applied in automotive and medical engineering due to their lightness and corrosion resistance [6]. Numerous parameters, such as shot diameter, air pressure, and shot peening time, affect the results of the shot peening process, and numerous experimental tests are required to study it [7–9]. Many studies have used modeling and numerical solution approaches, Taguchi experiment design, neural network, and artificial intelligence to assess the influence of factors in this process since these experiments are expensive and time-consuming [10–12].

Haghighi et al. studied the effect of shot peening time on the surface of AZ31 alloy. The researchers indicated that the grain size of the alloy's surface decreased from 520 angstroms in the raw specimen to 160 angstroms in the shot peened specimen during 80 minutes of shot peening process and increased the hardness and wear resistance of the AZ31 alloy surface due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [13]. Onal et al. studied the intensity and coverage of shot peening with Elman's test on the microstructure and mechanical properties of low carbon steel. The researchers indicated that fatigue life and hardness of the surface increased by increasing surface coverage and intensity of shot peening due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [14]. Moradi et al. used molecular dynamics modeling to investigate the influence of shot diameter and velocity parameters on mechanical properties and residual stress on the titanium's surface alloy in the shot peening process. They indicated that by increasing the

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value of shot diameter and velocity, the residual stress and hardness of the titanium surface increased due to creating a compact surface layer of titanium atoms on the surface [15]. In another study by Bagherifard et al., the effect of shot diameter, shot velocity, and coverage on the surface roughness of 39NiCrMo3 was investigated in the shot peening process by experimental tests and finite element simulation. They indicated that the surface roughness increased by increasing shot coverage due to the continuous and random impacts of the shots and the craters created on the surface [16]. In another study, Maleki studied the effect of shot peening parameters on the hardness and residual stress of surface in the severe shot peening process on the cast iron surface using a neural network and indicated that the estimated values in the neural network are in good agreement with the experimental results. The researchers indicated that with the shot peening process, the hardness of the surface increased due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [17]. In another study by Maleki and Sherafatnia, the effect of shot peening time and shot diameter on residual stress and surface hardness was investigated using neural network and experimental tests. The results predicted from the neural network are in good agreement with the experimental results. The researchers indicated that with the shot peening process, the residual stress and surface hardness increased due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [18]. In another study, Atal Pathak et al. studied the effect of shot peening parameters on the residual stress generated on the PMG Al 2024 alloy surface, applying the experimental design and Taguchi L16 array. The researchers showed that the effect of angle (coverage parameter) on the creation of surface residual stress is more than the shot diameter and distance from the surface in the shot peening process. The researchers indicated that the shot peening process increased surface hardness due to severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [19]. In another study, Thirumavalavan et al. studied the effect of shot peening parameters, such as shot diameter, shot velocity, and shot peening time on the hardness and final tensile strength of AA6061 alloy surface using the Taguchi L9 array in the shot peening process. They analyzed the signal-to-noise and indicated that the effect of shot peening time (coverage parameter) on surface hardness is higher than other parameters. Also, the researchers indicated that by the shot peening process, the surface hardness increased due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [20]. In another study by Moradi et al., the effects of shot peening time on titanium surface hardness and wear resistance were investigated. The researchers showed that the shot peening process led to the increase of 55, 57, and 63 % hardness of titanium surface and an increase of 32, 37, and 43 % of surface wear resistance in 20, 40, and 60 min due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface [21].

Therefore, according to these studies in the shot peening process, surface mechanical properties are improved due to severe plastic deformation, nanostructure, micro-strains, and grain refinement. There are two effective parameters in the shot peening process: intensity and coverage of shot particles on surfaces. These should be investigated because these parameters lead to deformation of surfaces, shot peening coverage divided to shot angle impinging and time. Shot peening intensity is divided to shot diameter and velocity. The researchers showed that coverage parameters affect residual stress and surface hardness more than other parameters. In the previous studies, the researchers investigated one or two effective parameters in the shot peening process, but in this study, the effect of all parameters of the shot peening process, including impinging angle, shot peening time, nozzle pressure, and shot diameter on the compressive residual stress, hardness, wear, and roughness on the surface of titanium alloy, has been investigated to complete the previous studies, applying experimental tests, Taguchi design (L9 orthogonal array) and signal-to-noise analysis to find the most effective parameter on each of the outputs.

2. Materials and method

2.1. Materials and shot peening process

According to the chemical composition in Table 1, Ti-6Al-4V titanium alloy was applied for shot peening operations. Each specimen was cut and prepared as circular surfaces with a diameter of 2.8 cm and a thickness of 3 mm utilizing electrical discharge machining. During the shot peening period and with varied shot sizes, a device with the ability to control the shot impinging angle and nozzle pressure was used, and the influence of these parameters on the compressive residual stress and mechanical characteristics of the surface was investigated.

2.2. Residual stress, hardness, and wear measurements

X-rays were applied to the surface of the specimens at a penetration depth of 20 microns after the shot peening process to study the strain and residual stress created on the surface, applying the

Table 1. Chemical composition of Ti-6Al-4V (wt.%)

V	Al	Sn	Zr	Mo	C	Si	Cr	Fe	Nb	Ti
4.02	5.16	00615	0.0038	0.0052	0.369	0.22	0.099	0.112	0.0386	90

Table 2. Shot peening experiment design with 4 factors and 3 levels

Factors	Levels		
	1	2	3
A: Shot diameter (mm)	0.4	0.6	1
B: Impinging angle θ	30	60	90
C: Nozzles air pressure (bar)	1	2	4
D: Shot peening time (min)	20	40	60

XRD device ASENWARE and model AW-XDM300 with an X-ray wavelength of 1.542 angstroms, and the standard method of X-ray diffraction of Bragg's law (Eq. (1)) [22], and the reflected rays were received where there is the most intensity. X-rays have a specific wavelength, and any change in the distance among the crystal plates (d) displaces the reflection angle (θ). The appropriate diffraction curve was selected for the residual stress in terms of the appropriate geometric shape among the diffraction curves. Based on Bragg's law, Eq. (1), the distance among the crystal plates is calculated in terms of θ (X-ray reflectance angle). The $(d - d_0)/d_0$ graph in terms of $\sin^2\psi$ was then plotted with angles ψ = –10, –20, –30, 0, 15, 30, 45 for all specimens by determining the position of the diffraction curve at each angle ψ (the angle between the vector perpendicular to the plane and the bisector of the angle reflected). The residual stress at the surface of the titanium alloy specimens was calculated according to the slope and width from the origin of the plotted lines and Eq. (2) [23]. The residual stress test was performed on a peak with an angle of $2\theta \cong 76.5°$. The surface residual strain values were then calculated according to the values of compressive residual stress and modulus of elasticity of titanium alloy:

$$n\lambda = 2d\sin\theta, \tag{1}$$

where d is the distance among the crystal plates, θ is the angle of reflection, n is the number of reflections, and λ is the X-ray wavelength in angstroms:

$$\sigma_\Phi = \frac{E\,(d_\psi - d_0)}{(1+\upsilon)\sin^2\psi \times d_0}, \tag{2}$$

where σ_Φ is compressive residual stress, d_0 is the distance among the crystal plates at an angle of $\psi = 0$, d_ψ is the distance among the crystal plates at an angle ψ, E is the modulus of elasticity, and ν is Poisson's coefficient.

The grain size value was calculated using Scherer's equation (Eq. (3)), applying the X-ray diffraction pattern and the peak width in the X-ray diffraction pattern at half the maximum height [24]:

$$d = \frac{0.9\lambda}{\beta\cos\theta}, \tag{3}$$

where d is the crystal size, λ is the X-ray wavelength, θ is half the angle at the maximum height (radians), and β is the selected peak width at half the maximum height in the diffraction pattern.

Moreover, the VEGA-TESCAN-XMU model was applied to study the microstructure formed on the surface of SEM. Vickers method and Innova test were used to measure the hardness. The applied force in the hardness test was 300 grf, and the hardness intervals were at a depth of 100 microns. The pin-on-desk method was applied to examine the wear behavior of the samples. FESEM model MIRA 3TESCAN-XMU was employed to study the wear mechanism. Additionally, surface roughness was investigated at a distance of 10 mm on the surface.

2.3. Taguchi method for the design of experiments

Taguchi test design method is an efficient way to save time and laboratory costs to examine the effect of all problem parameters on its output results. An experimental design was performed for the shot-peened specimens. The Taguchi L9 orthogonal array was selected by considering the number of factors and their levels (4 factors and 3 levels) shown in Table 2. Then, a more effective factor on each output was investigated by signal-to-noise analysis.

Table 3: Results of residual stress and mechanical properties Taguchi L9 orthogonal array

Specimens	Shot diameter (mm)	Impinging angle (°)	Nozzles air pressure (bar)	Shot peening time (min)	Value of compressive residual stress (MPa)	Crystallite size (nm)	Micro-strains ($\times 10^4$)	Surface hardness HV	Surface mass loss (mgr)	Roughness (µm)
1	0.4	30	1	20	779	31.3	33.2	405	0.0064	1.3
2	0.4	60	2	40	1121	26.8	41.1	465	0.0049	3.2
3	0.4	90	4	60	1327	19.6	53.6	497	0.0038	4.8
4	0.6	30	2	60	975	28.1	35	435	0.0051	2.3
5	0.6	60	4	20	1032	27.6	35.6	454	0.0050	2.4
6	0.6	90	1	40	1211	20.3	53.2	490	0.0039	3.5
7	1	30	4	40	847	28.6	34.1	410	0.0060	1.5
8	1	60	1	60	1132	26.5	50.6	478	0.0047	3.3
9	1	90	2	20	1141	23.4	52.5	485	0.0040	3.4
10(Raw)	–	–	–	–	–	150	9.6	265	0.0088	1.1

Table 4. Response (residual stress) for signal-to-noise ratios larger is better

Level	Time (min)	Pressure (bar)	Impinging angle (°)	Shot diameter (mm)
1	59.75	60.19	58.72	60.43
2	60.40	60.64	60.78	60.57
3	61.10	60.43	61.76	60.26
Delta	1.35	0.45	3.03	0.31
Rank	2	3	1	4

3. Results and discussion

By executing the shot peening operation and applying the Taguchi L9 orthogonal array, it was stated that the values of residual stress, micro-strain, grain size, and mechanical characteristics of the surface, including hardness, mass loss, and roughness, are in line with Table 3.

3.1. Compressive residual stress

After the shot peening process, the values of residual stress generated on the surface of 9 shot peened specimens were obtained by diffraction of X-rays at a depth of a maximum of 20 microns from the surface.

Figure 1 shows the mean values of residual stress at each level of shot peening factors, shot diameter, pressure, angle, and shot peening time by applying Taguchi analysis in the Minitab software. There is more difference in the mean residual stress value for the impinging angle factor compared to other factors and shows the more significant effect of this parameter. Residual stress is created in the shot peening process as a result of severe plastic deformation during the process and the creation of a nanostructured surface layer; if its amount is greater, the surface strength will be greater, and the optimal surface will be obtained; thus, signal to noise used in residual stress analysis. According to Table 4, the shot impinging angle has the greatest effect on the amount of residual stress. The effect of the shot peening time, pressure, and the shot diameter are in priorities 2, 3, and 4, respectively. Figure 2 shows the effect of each parameter of impinging angle, shot peening time, pressure, and shot diameter

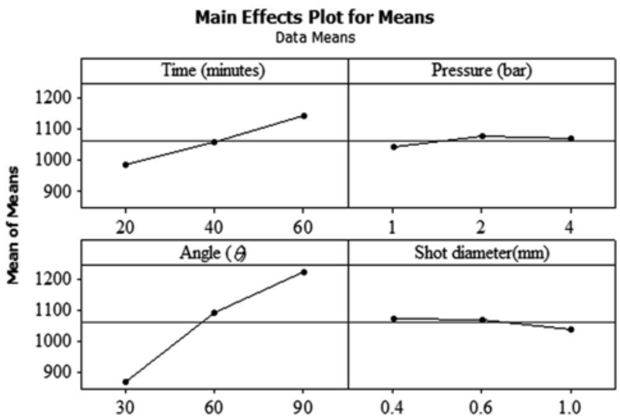

Fig. 1. Main effect plot of SN ratios for compressive residual stress.

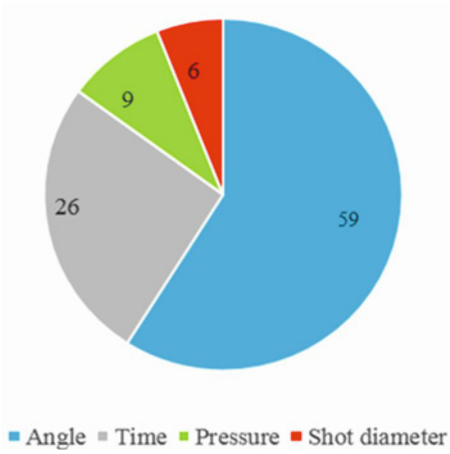

Fig. 2. Percentages of the effect of each parameter on compressive residual stress.

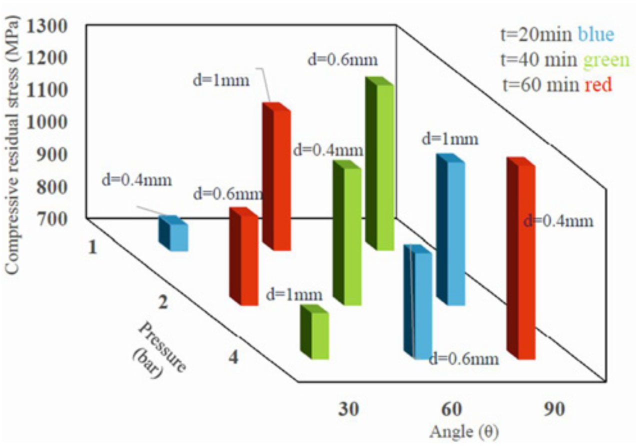

Fig. 3. The value of compressive residual stress compared in each specimen.

on the residual surface stress, which is 26, 9, 59, and 6 %, respectively. Figure 3 shows the residual stress values of each specimen and indicates that residual stress values of specimens with a 90-degree angle are higher than other specimens, which indicates a more significant effect of the impinging angle compared to other parameters on the residual stress.

Impinging angle and shot peening time are two significant factors of surface coverage factor based on Figs. 1–3 and Table 4. The impinging angle has the greatest effect on the residual stress, and if the angle is higher and reaches 90°, the probability of successive collisions of the shot and higher coverage near the surface will be higher. Thus, the shot coverage on the surface increases; consequently, the residual stress increases in the following priority with the time duration of 60 min.

The results of this study showed that impinging angle and time duration (coverage factors) affect more

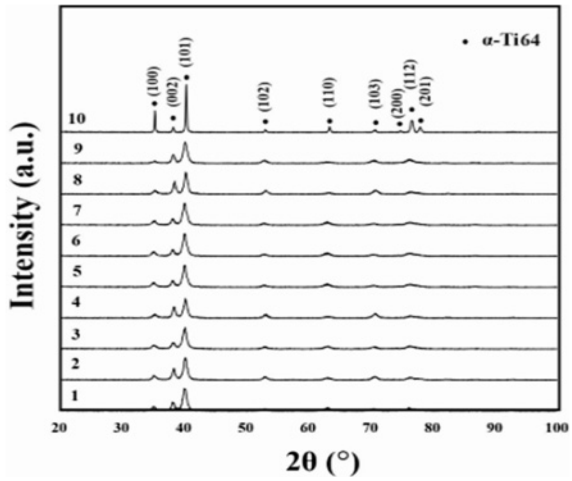

Fig. 4. X-ray diffraction pattern for raw and shot peened specimens.

than shot diameter and velocity (intensity factors) on compressive residual stress of titanium surface and are in agreement with the results achieved by Maleki et al., who indicated that coverage factor affects more than intensity on surface's residual stress in AISI 1016 alloy [25]. In another study, Kumar et al. studied the effect of pressure parameters and shot peening time on residual surface stress in titanium alloy by designing a Taguchi L16 orthogonal test and explained that the effect of shot peening time, which is one of the factors of the surface coverage, is more than the pressure and increasing the shot peening time from 5 to 20 min increases the residual stress from 765 MPa to 825 and 870 MPa at depths of 25 and 40 microns of the surface [26].

3.2. Grain size

X-ray diffraction (XRD), according to Fig. 4, was obtained for the raw sample and 9 shot peened specimens of titanium alloy. As shown in Fig. 4, if the grains become finer, the width of the peak will be increased, and the intensity of the peak will be decreased. During the shot peening process, severe plastic deformation causes the grains to become fine and form a compact layer of nanocrystallites on the surface of the titanium alloy [4, 5]. Figures 5 and 6 show the SEM images of the raw specimen and the shot peened specimens 1 and 3. Figure 6 presents the grain refinement and deformed layers of the surface for specimens 1 and 3, respectively, which have the minimum and maximum deformation layers of the surface compared to the raw specimen (Fig. 5). The deformation of the surface layer of titanium alloy for specimens 1 and 3 is 250–300 and 500–600 microns, respectively. Grain refinements and surface deformation of titanium alloy are due to severe plastic deformation on the surface

Table 5. Response (hardness) for signal-to-noise ratios larger is better

Level	Time (min)	Pressure (bar)	Impinging angle (°)	Shot diameter (mm)
1	53.00	53.18	52.39	53.14
2	53.14	53.28	53.36	53.24
3	53.43	53.11	53.82	53.19
Delta	0.43	0.17	1.42	0.10
Rank	2	3	1	4

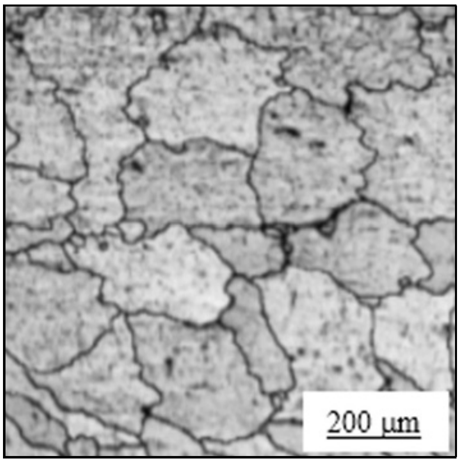

Fig. 5. SEM image for a raw specimen.

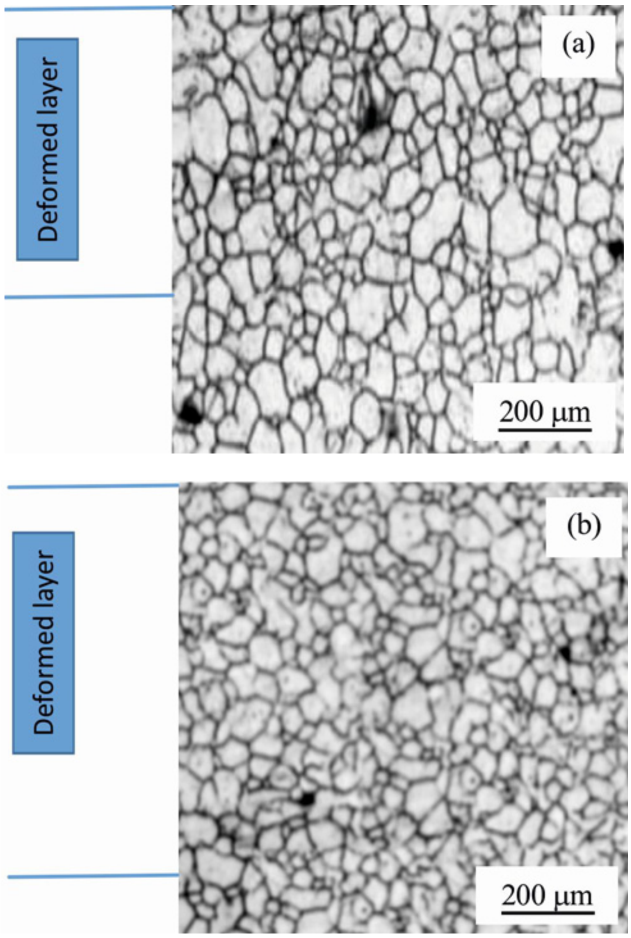

Fig. 6. SEM images, the effect of shot peening process on surface microstructures: (a) specimen 1 and (b) specimen 3.

of specimens during the shot peening process. Wong et al. studied the influence of high-energy shot peening operations and significant plastic deformation during the process on grain refinements in titanium alloy. The researchers indicated that the grain size on the surface decreased from 200–300 microns to 20–30 microns. After the shot peening operation, the depth of the hardened layer from the surface of the titanium alloy became 170–150 microns [27].

3.3 Hardness of the surface

Figure 7 indicates the mean values of surface hardness at each level of shot peening factors, impinging angle, shot peening time, shot diameter, and pressure in Minitab software that there is more difference in the mean values of surface hardness in the shot impinging angle factor compared to other factors and shows the more significant effect of this parameter on surface hardness. Based on the desirability of more hardness and the strength of the surface, the larger signal-to-noise ratio is a better option used to analyze the surface hardness. According to Table 5, the shot impinging angle has the greatest effect on the surface hardness, and the shot peening time, the pressure, and the shot diameter are in priorities 2, 3, and 4, respectively. Figure 8 shows the effect of each parameter of impinging angle, shot peening time, pressure, and shot diameter on the surface hardness, which is 8, 20, 67, and 5 %, respectively. Figure 9 shows the surface hardness values of each specimen and reveals that specimens with a 90-degree angle have a higher surface hardness value than other specimens, indicating that the impinging angle has a greater influence on the surface hardness than other parameters. The impinging angle and shot peening time duration are the two critical parameters in determining coverage and, therefore, surface hardness. Table 5

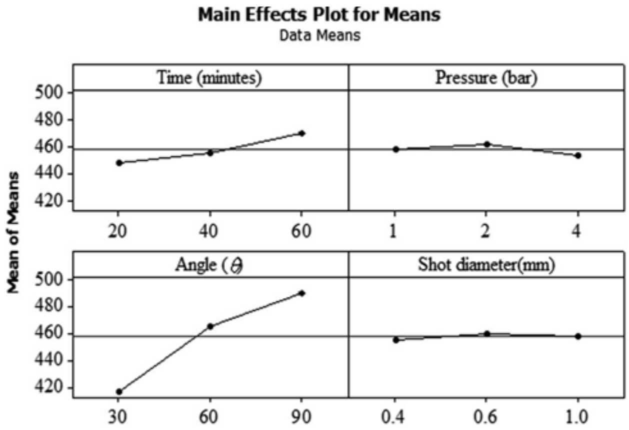

Fig. 7. Main effect plot for means of surface hardness.

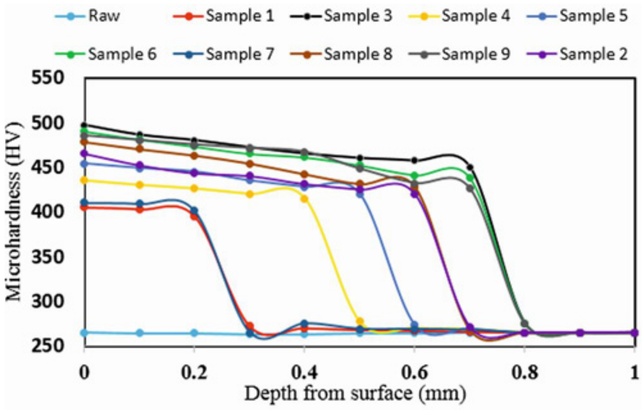

Fig. 10. Surface hardness values for the raw and shot peened specimens, up to a depth of 1000 microns.

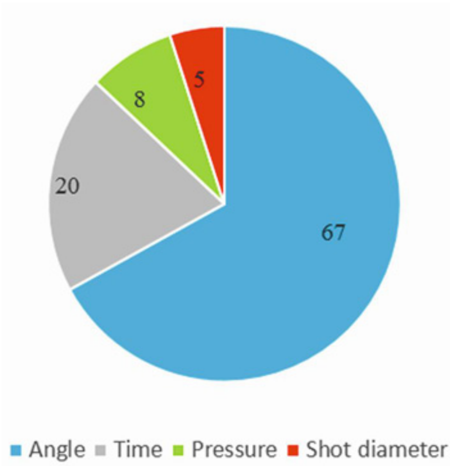

Fig. 8. Percentages of parameters effect on hardness.

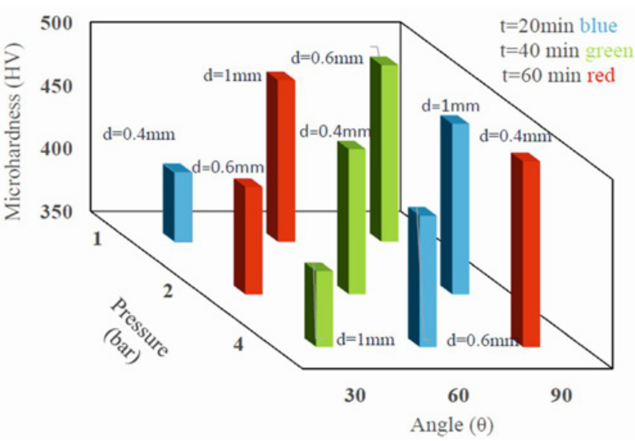

Fig. 9. The value of surface hardness compared in each specimen.

and Figs. 7–9 show that the impinging angle has the greatest effect on the surface hardness, and the optimal surface achieved the greater hardness with an angle of 90°, and time duration of 60 min in the next priority. The results of this study showed that impinging angle and time duration (coverage factors) affect more than shot diameter and velocity (intensity factors) on the hardness of titanium surface and are in agreement with the results achieved by Maleki et al., who indicated that coverage factor affects more than intensity on surface hardness in AISI 1016 alloy [25].

Figure 10 shows the hardness values of the raw specimen and 9 shot peened specimens up to a depth of 1000 microns from the surface of the titanium alloy. The depth of the hardened layer in the shot peened specimens 1 and 3 is about 200 and 500 microns, respectively, which is in good agreement with the depth of the deformed layer (grain refinement) from the surface in Fig. 6. After these intervals, the hardness becomes almost constant and equal to the hardness of the raw specimen. Surface hardness values are achieved 405 and 497 HV, respectively, by the shot peening process in specimens 1 and 3, which have minimum and maximum hardness, and the hardness of these specimens increased by 53 and 87 %, respectively, compared to raw specimen, due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface. The results achieved by this study are in agreement with the results achieved by Zhou et al., who studied the effect of the ultrasonic shot peening process on the surface hardness of titanium alloy. The researchers showed that increasing the shot peening time from 5 to 800 s improves the surface hardness to 352.4 HV, which is almost 75 % higher than the raw specimen's hardness. This is due to the creation of grain refinements, nanostructure, and micro-strain on the surface of titanium alloy [28].

Table 6. Response (mass loss) for signal-to-noise ratios smaller is better

Level	Time (min)	Pressure (bar)	Impinging angle (°)	Shot diameter (mm)
1	45.95	46.20	44.72	46.16
2	46.27	46.67	46.26	46.68
3	46.94	46.29	48.18	46.32
Delta	0.99	0.46	3.46	0.52
Rank	2	4	1	3

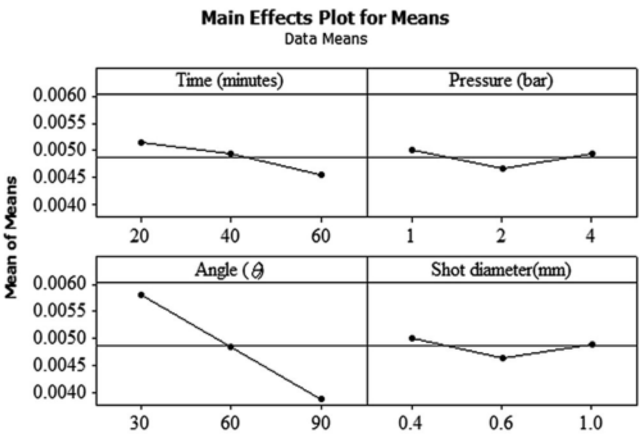

Fig. 11. Main effect plot for means of mass loss.

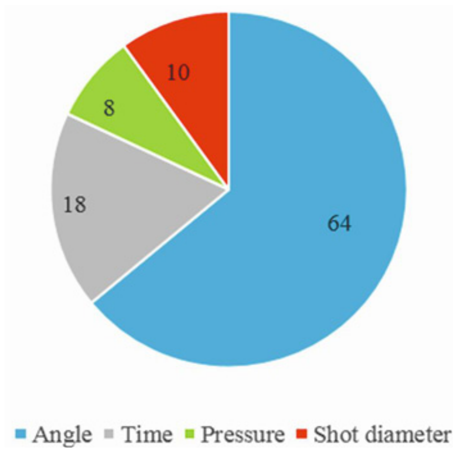

Fig. 12. Percentages of parameters effect on mass loss.

3.4. Wear of surface

Figure 11 shows the mean values of mass loss at each level of shot peening factors, impinging angle, shot peening time, shot diameter, and pressure in the Minitab software that there is more difference in the mean values of mass loss in shot impinging angle compared to other factors and shows the more significant effect of this parameter on the mass loss. In the shot peening process, less mass loss of specimens and, consequently, more wear resistance is desirable; therefore, the signal-to-noise ratio smaller is better to analyze the effect of shot peening parameters on the mass loss. According to Table 6, the shot impinging angle has the greatest effect on the mass loss, and the shot peening time, the pressure, and the shot diameter are in priorities 2, 3, and 4, respectively. Figure 12 shows the effect of each parameter of impinging angle, shot peening time, pressure, and shot diameter on the mass loss, which is 10, 18, 64, and 8 %, respectively. The mass loss values of each specimen are shown in Fig. 13. Because the mass loss values of specimens with a 90-degree angle are smaller than those of other specimens, and therefore the wear resistance is greater, this implies that the impinging angle has a greater influence on mass loss than other factors. Impinging angle and shot peening time are the two key factors in coverage and, consequently, higher wear resistance and lower mass loss. According to Figs. 11–13 and Table 6, the impinging angle significantly affects the mass loss from the surface, and with an angle of 90°, and in the next priority, a time duration of 60 min; the wear resistance of the surface is optimized.

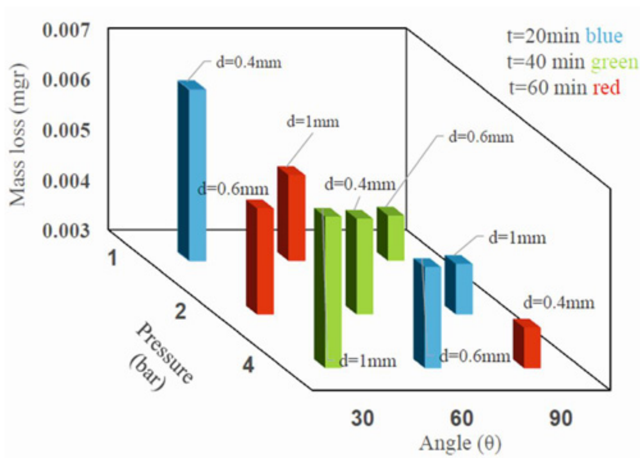

Fig. 13. The value of mass loss compared in each specimen.

As Fig. 14 shows, the amount of mass loss from the surface is shown after the shot peening operations and by performing pin-on-disk test on the raw and shot peened specimens over a distance of 500 m on

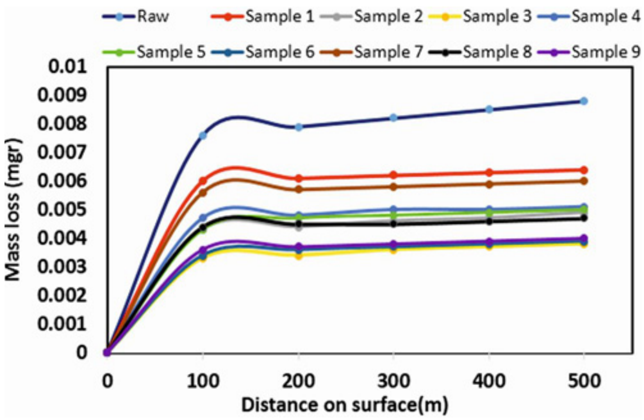

Fig. 14. Correlation between the amount of mass loss and distance covered on the surface for raw and shot peened specimens.

the surface of titanium alloy. As it is obvious, increasing the distance on the specimens' surfaces increases the mass loss. The specimens with the greatest surface hardness have the least mass loss from the surface and, as a result, the best resistance to surface wear. Samples 1 and 3 have a maximum and minimum mass loss from the surface, and the wear resistance on the surface of these specimens compared to the raw specimen (which has a mass loss of 0.0088 g) has increased by 27 and 57 %, respectively, due to the creation of severe plastic deformation, nanostructure, micro-strains, and grain refinement on the surface, by shot peening process. The results of this study are in agreement with the results achieved by Takiso et al., who studied the effect of the shot peening process on the wear resistance of the titanium alloy surface. The researchers showed that increasing the shot peening time decreased the mass loss from the titanium surface from 0.6 to 0.18 mg and caused a 70 % increase in surface wear resistance due to the grain refinements in a compact layer on the surface, the formation of a nanostructured surface layer, and the creation of micro-strain on the surface of the titanium alloy [29].

3.5. Wear mechanism

Figure 15 indicates the wear mechanism of specimens 1 and 3, which have minimum and maximum surface hardness. Adhesive and abrasive mechanisms are visible on the surface of these samples. Furthermore, the adhesive wear was reduced by increasing the surface hardness in the shot peening process. Sample 3 has the lowest adhesive wear owing to the deformed layer's greater hardness and depth (grain refinement) than the titanium alloy's surface. In multi-layered or distributed specimens, adhesive wear is obvious. In a study, Yang et al. indicated that the increase in surface

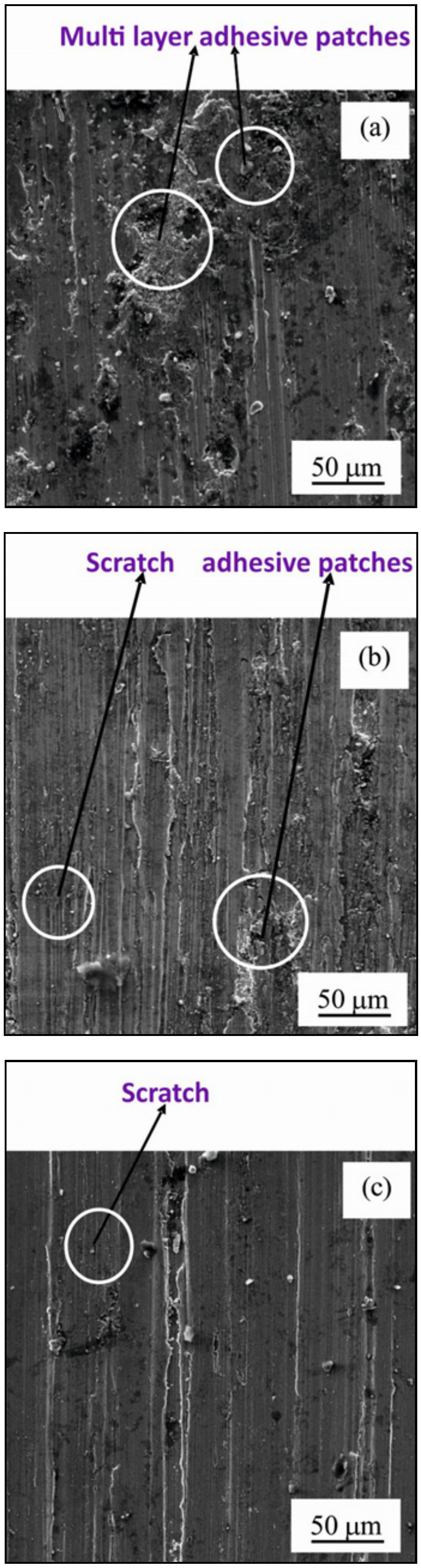

Fig. 15. The surfaces wear for the raw and shot peened specimens: (a) raw specimen, (b) specimen 1, and (c) specimen 3.

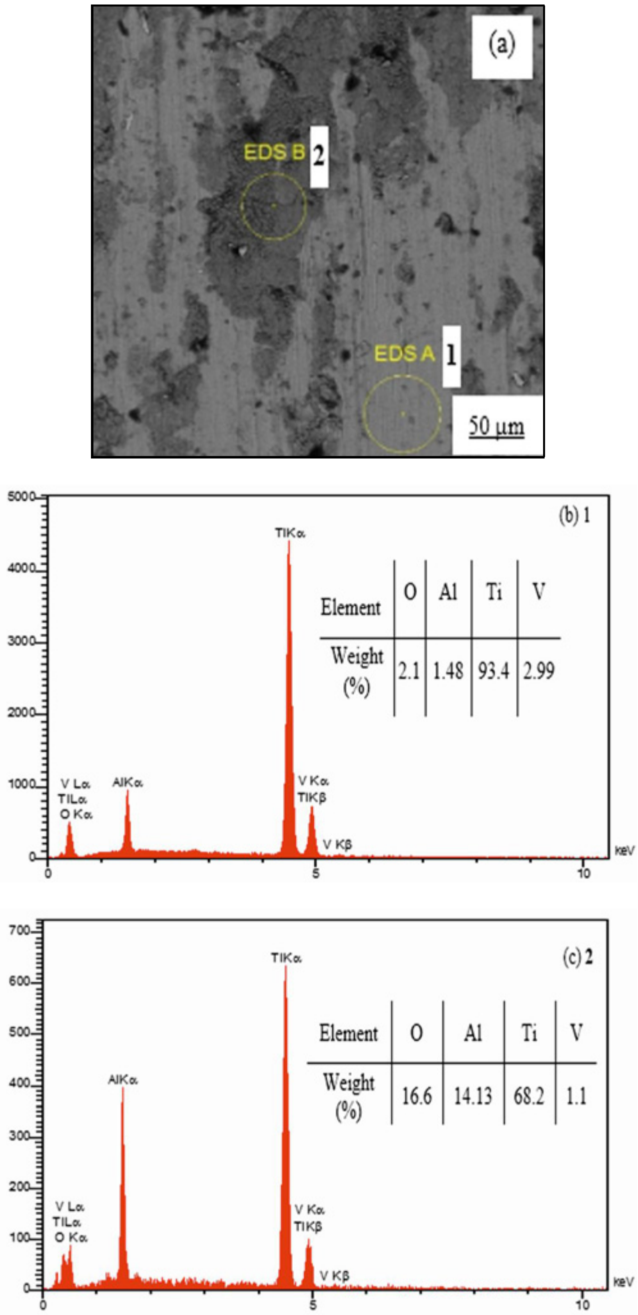

Fig. 16. Image of surfaces wear and EDS analysis for shot peened specimen 3: (a) wear surface, (b) and (c) EDS analysis at points A and B.

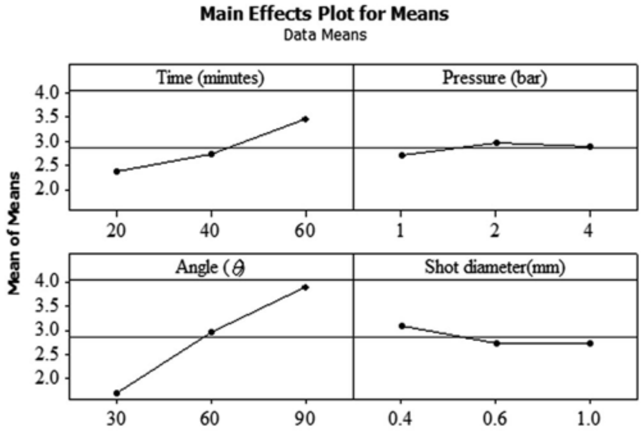

Fig. 17. Main effect plot for means of roughness.

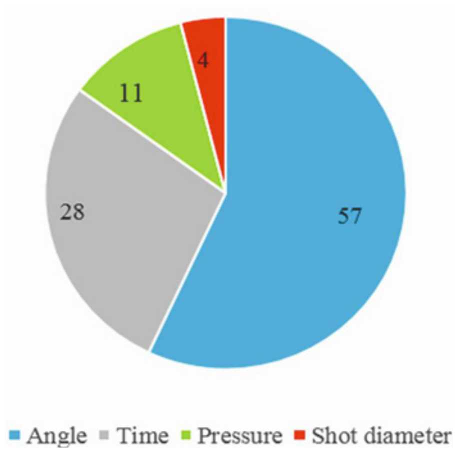

Fig. 18. Percentages of parameters effect on roughness.

hardness is mainly because of an increase in adhesive wear resistance [30].

For further investigation, EDS analysis was performed on points A and B of specimen 3. According to Fig. 16, the wear mechanism is demonstrated on the non-adhesive surface (point A) and the adhesive surface (point B). As it is obvious, the oxidation rates of points A and B are 2.1 and 16.6 %, respectively. Hence, due to the increase in temperature during wear, tribochemistry wear has occurred in the adhesive areas of point B in Fig. 16a.

3.6. Roughness of surface

Figure 17 indicates the mean values of roughness at each level of shot peening factors, impinging angle and shot peening time, shot diameter, and pressure that the effect of impinging angle is more significant than other parameters on the surface roughness. Sometimes to join two metal surfaces to each other, the base surface should have an appropriate roughness value, although excessive roughness is not desirable. Therefore, larger signal-to-noise ratios can better analyze the effect of shot peening parameters on the surface roughness. According to Table 7, the shot impinging angle has the greatest effect on the surface roughness, and the shot peening time, the pressure, and the diameter of the shot are in priorities 2, 3, and 4, respectively. Figure 18 shows the effect of each parameter of impinging angle, shot peening time, pressure, and the

Table 7. Response (roughness) for signal-to-noise ratios larger is better

Level	Time (min)	Pressure (bar)	Impinging angle (°)	Shot diameter (mm)
1	6.838	7.844	4.345	8.669
2	8.169	9.322	9.359	8.573
3	10.410	8.250	11.712	8.174
Delta	3.572	1.479	7.367	0.495
Rank	2	3	1	4

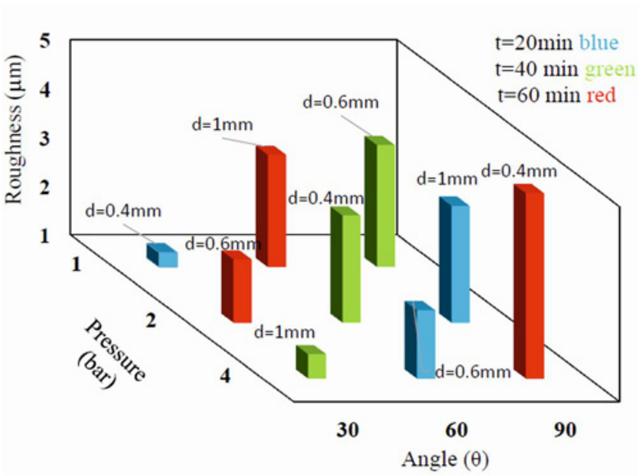

Fig. 19. The value of roughness compared in each specimen.

diameter of the shot on the surface roughness, which is 11, 28, 57, and 4 %, respectively. Figure 19 shows the surface roughness values of each specimen and indicates that the surface roughness values of specimens with a 90-degree angle are higher than of other specimens; it indicates a more significant effect of the impinging angle compared to other parameters on the surface roughness. Impinging angle and shot peening time are the two key factors in coverage and consequently higher surface roughness. Figures 11 and 17, Table 7, and Figs. 18 and 19 show that the impinging angle significantly affects the surface roughness. With an angle of 90°, and in the next priority, a time duration of 60 min, the roughness of the surface is optimized. The results of this study are in agreement with the results achieved by Kumar et al., who studied the effect of the shot peening time and pressure parameters on the surface roughness in the titanium alloy by designing the Taguchi L16 orthogonal array test. The researchers indicated that the effect of shot peening time, as a significant factor in shot coverage on the surface, is more than other parameters on surface roughness [26].

Figure 20 shows the SEM images of the surface of the raw specimen and the shot peened specimens 1 and 3 of the titanium alloys, which have the minimum

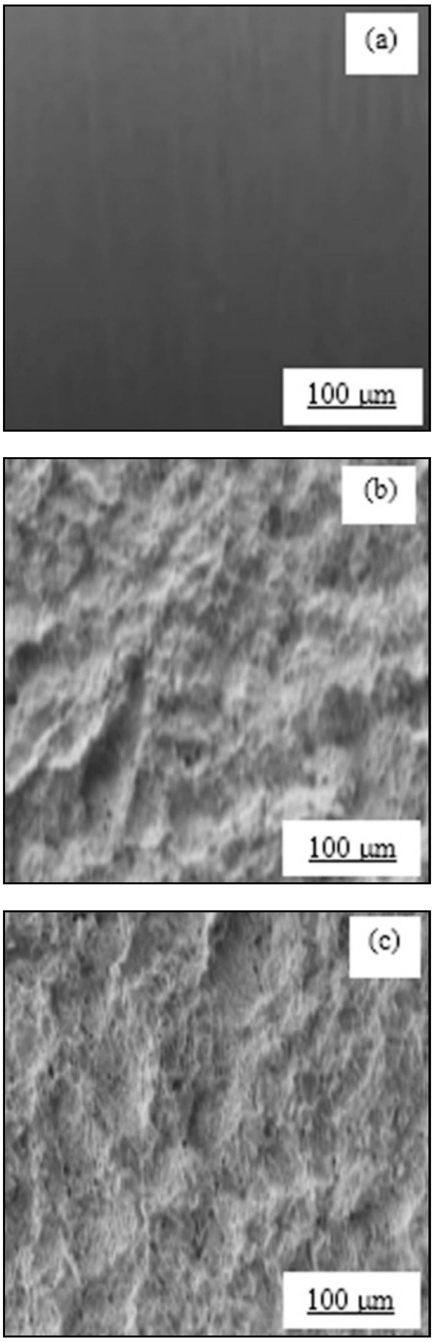

Fig. 20. SEM images, surface roughness for the raw and shot peened specimens: (a) raw specimen, (b) specimen 1, and (c) specimen 3.

and maximum roughness values. Surface roughness increased from 1.1 microns in the raw specimen to values of 1.3 and 4.8 microns in these specimens. The surface roughness increased due to the continuous and random impacts of the shots and the creation of craters on the surface of the titanium alloy.

The results achieved by this study are in agreement with the research achieved by Zhou et al., who studied the effect of the shot peening process on surface roughness. According to the researchers, the surface roughness was enhanced from 1.4 microns in the raw specimen to 3.6 microns in the 700-second shot peened specimen owing to the random collisions of shot to the surface and the formation of craters on the titanium alloy's surface [31].

4. Conclusions

The shot peening process is the method to improve surface mechanical properties due to the creation of severe plastic deformation, nanostructure, compressive residual stress, micro-strains, and grain refinement on the surface, used in medical applications and some industries such as aero-spaces.

In this study, the effect of all parameters in the shot peening process on compressive residual stress, hardness, wear resistance, and surface roughness of Ti-6Al-4V alloy was investigated. The experimental tests, Taguchi L9 array test design, and signal-to-noise analysis were applied for this goal.

The results showed that:

1. Among the effective parameters in the shot peening process, the impinging angle was a key factor and affected the compressive residual stress, hardness, wear resistance, and surface roughness of the titanium alloy by 59, 67, 64, and 57 %, respectively.

2. The hardness of specimens 1 and 3 (with minimum and maximum hardness) increased by 53 and 87 %, compared to the raw specimen, respectively, due to the creation of severe plastic deformation, nanostructure, compressive residual stress, micro-strains, and grain refinement on the surface.

3. The wear resistance of specimens 1 and 3 (with maximum and minimum mass loss) increased by 27 and 57 %, compared to the raw specimen, respectively, due to the creation of severe plastic deformation, nanostructure, compressive residual stress, micro-strains and grain refinement on the surface.

4. The wear mechanism of the specimens was abrasive and adhesive. The amount of adhesive wear decreased in the shot peening process; the tribochemistry wear mechanism was also observed in the adhesive areas.

5. The surface roughness of the shot-peened specimens increased compared to the raw specimen due to the continuous and random impacts of the shots and the craters created on the surface of the titanium alloy.

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