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Research article

Effects of the secondary shot in the double shot peening process on the residual compressive stress distribution of Ti–6Al–4V

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ABSTRACT

Double shot peening is the development of shot peening by shooting large media as a first shot and re-shooting again with smaller media as a second shot in order to achieve high residual compressive stress and hardness at the surface, while the in-depth effect can still be maintained. This research aims to examine the effect of media type and media size when used in the second shot of double shot peening on hardness, roughness, and residual stress to identify the suitable conditions and compare them with single shot peening, such as conventional shot peening and fine shot peening, which was used as the first shot and second shot. Ti–6Al–4V was used as the substrate material, while various diameter sizes of silica and SUS304 media were selected as the media for the second shot in the process. The results showed that in the case of the larger size of silica media in the second shot of double shot peening, the hardness and residual compressive stress on the surface clearly increased more than with the smaller media due to the higher Almen intensity, which affected impact energy. On the other hand, when shooting with SUS304 media as a second shot, the increment of residual compressive stress and hardness, including roughness reduction on the surface, showed less effect than was the case for silica media, due to the lower Almen intensity, which affected the impact energy transfer. This research found that the condition of shooting with 80 μm of silica media as the second shot could generate the highest hardness and residual compressive stress on the surface, which increased by 14% and 53%, respectively, while roughness was decreased by 20% when compared with single shot peening.

1. Introduction

Shot peening is a surface modification process performed by shooting spherical media to material surfaces at high speed, which helps to increase fatigue strength by generating many dimples and plastic deformations on the surface, resulting in an increase in residual compressive stress and hardness [1, 2, 3, 4]. When comparing this process to other surface modification processes, shot peening is more highly beneficial than others in terms of surface mechanical properties, which maintained its properties without any flaking off. Shot peening does not generate a layer on the surface, but permanently changes the surface properties of the material, resulting in higher durability when compared to other surface modification processes. Moreover, shot peening is more applicable towards controlling biocompatibility than other surface modification processes as there are fewer parameters to control. Therefore, shot peening is suitable for use in biomaterials for enhancing the surface mechanical properties of medical devices than other surface modification processes. However, the residual compressive stress found in this process is not smooth, so it is not fitted to resist tensile stress in the bending stress diagram, which is high on the surface and gradually decreases in-depth from the surface. When shooting with large media or high Almen intensity shot, the maximum residual compressive stress is generated at deep positions, while near the surface, a lower residual compressive stress is generated. Moreover, the large media would generate high roughness on surfaces, which can in turn cause lower fatigue strength [5]. On the other hand, when shooting with small media or low Almen intensity, the maximum residual stress is generated near the surface, but with a lesser effect at in-depth positions [6, 7]. Accordingly,

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one significant method to improve this process is called double shot peening. This method begins with shooting large media in the first shot followed by small media in the second shot. The result is a high value for residual compressive stress near the surface with a remaining depth effect further from surface [8, 9], which is able to increase fatigue strength [5]. Moreover, some research papers stated that the hardness was also increased after the double shot peening process [10, 11]. However, there are only a few papers, which have reported on the residual compressive stress found from this method as well as the effect of media type and media size of the secondary shot.

Titanium alloy, Ti–6Al–4V, was used in this research since there are many applications of Ti–6Al–4V included in medical devices, such as orthopedic devices, with the properties of having high strength, biocompatibility, and corrosion resistance [12, 13]. However, some reports indicated failure of devices, such as fracture and deformation. The fractures come from the cycle load of bending that leads to failure by fatigue [14, 15, 16, 17]. According to various journal papers, shot peening can increase bending strength and bending fatigue due to its higher residual compressive stress and hardness at the near surface, which receives the highest stress from the bending load [2, 4, 18, 19].

Based on the problems related to the use of Ti–6Al–4V in medical devices, shot peening is one of the surface modification methods that might be helpful in solving those problems. However, non-uniform residual compressive stress and high roughness are still the problems arising in the shot peening process. This research aims to maintain high residual compressive stress from the surface to the deeper surface and decrease the surface roughness by double shot peening. Furthermore, comparisons will be drawn with single shot peening based on some results from previous research [7]. Moreover, this research could be a guideline on how to select the media type and size of second shot to enhance the effectiveness of double shot peening to maintain the uniform residual compressive stress and hardness both on the surface and in-depth surface, while roughness is reduced. SUS304 and silica media were selected since both materials are biocompatible following SAE j3020 standard [20] and have different densities and hardness.

2. Experimental methods and materials

There were four sections of experiments in this paper to describe the effects of the secondary shot in the double shot peening process. For the first section concerning surface morphology and roughness, an optical microscope was utilized to observe the surface of the specimens. In order to evaluate the change of surface by single and double shot peening, the arithmetical mean deviation (Ra) and mean width of the profile elements (Rsm) were measured by roughness tester. In order to investigate the effect of each shot peening process in the second and third sections, not only data from double shot peening, but also those of single shot peening from the first shot and second shot, which are called conventional shot peening and fine shot peening, were also used for comparison in this research. In the second section, for an analysis of residual compressive stress and full width at half maximum (FWHM), which relates to the domain size of material [21, 22], X-ray diffraction (XRD) measurements were taken. In the third section, Vicker's hardness test was conducted in order to measure the micro hardness on the top surface and cross-sectional surface of the materials at different depths from the surface. In the final section, Energy Dispersive X-Ray Spectroscopy (EDS) was used to detect and identify the residual elements, which remained on the surface after shot peening and might somehow be of concern when using the medical device. Further details of each experimental section are described below.

2.1. Materials

Titanium alloy, Ti–6Al–4V medical grade (Gr23), was obtained from Xinxiang Jinxing Metal Corp, China. The 3.5 mm flat plate from the hot rolling process with a chemical composition of 3.85 V, 5.6 Al, other <0.37 and 90.18 Ti (bal) in wt% was used in this research. The specimen was cut in sizes of 35 mm × 35 mm and its surface was cleaned using an ultrasonic bath. Recorded measurements of 0.8915 μm for arithmetical mean deviation (Ra) with mechanical properties of 1025 MPa in tensile stress, 1006 MPa of yield stress, 128 GPa of elastic modulus and 373 HV of hardness were reported as received.

2.2. Shot peening treatment

The process of double shot peening started from shooting a large media in the first shot, which was 400 μm of SUS304 media, until 100% of the peening coverage was reached, which means all surface areas had been impacted by the media, followed by shooting again with a smaller media size in the second shot with 100% peening coverage. To compare the effects of media type and size, SUS304 and silica media with various sizes between 40 μm to 100 μm were selected since these two materials have differences in density and hardness, which can affect the Almen intensity and impact energy transfer. It is noted that all media used in this research were of a spherical shape, which do not remove the layer of the material surface. Moreover, in order to understand the effects of shot peening in each condition of the double shot peening process, single shot peening from the first and the second shot, called conventional shot peening (SP) and fine shot peening (FSP), were individually used to compare with the double shot peening process, while the code name of single shot peening and double shot peening in each condition is shown in Table 1. Other parameters were controlled to clarify the effects of media size and type; i.e., the pressure to the media was controlled at 0.5 MPa, the distance and the angle between nozzle and material were maintained at 20 cm and 90°, respectively. The process was performed in a cabin controlled at atmospheric pressure with dust prevented from entering from outside. The Almen intensity value, showing the impact energy of shot peening in each media condition, was measured by shooting each media on an Almen strip and measuring the bending curve in units of millimeters [23, 24], with some results as reported in previous research [7], and shown in Table 2. The letters N and A in the value of Almen intensity represent the thickness of the Almen strip, which is 0.76

Table 1. Conditions of shot peening.

Code Name	Shot peening process	First Shot		Second Shot	
		Media Type	Media Size	Media Type	Media Size
SP SUS400	Conventional shot peening	SUS304	400 μm	-	-
FSP SUS50	Fine shot peening	SUS304	50 μm	-	-
FSP SUS100	Fine shot peening	SUS304	100 μm	-	-
FSP Si40	Fine shot peening	Silica	40 μm	-	-
FSP Si80	Fine shot peening	Silica	80 μm	-	-
DSUS50	Double shot peening	SUS304	400 μm	SUS304	50 μm
DSUS100	Double shot peening	SUS304	400 μm	SUS304	100 μm
DSi40	Double shot peening	SUS304	400 μm	Silica	40 μm
DSi80	Double shot peening	SUS304	400 μm	Silica	80 μm

Table 2. Almen intensity from each media condition.

Media Type	Media Size	Pressure	Distance and Angle	Almen Intensity
SUS304	50 μm	0.5 MPa	20 cm, 90°	0.154 mmN
SUS304 [7]	100 μm	0.5 MPa	20 cm, 90°	0.194 mmN
SUS304 [7]	400 μm	0.5 MPa	20 cm, 90°	0.178 mmA
Silica	40 μm	0.5 MPa	20 cm, 90°	0.095 mmN
Silica [7]	80 μm	0.5 MPa	20 cm, 90°	0.140 mmN

mm and 1.27 mm, respectively. The Almen intensity measurement showed that SUS304 media was able to generate higher Almen intensity than silica media with similar media size. In other words, it can be said that the media with higher density can generate even higher impact energy [23]. The Almen intensity of media with larger size was also higher than that of media with smaller size because of the mass of the media, which is higher [23, 24].

2.3. Surface morphology and roughness

An optical microscope (Olympus) was used to examine the surfaces at 20 times magnification to compare between shot peening and double shot peening in each condition. The roughness tester from Kosaka Laboratory Ltd. was chosen to measure the roughness profile with the length of 4.00 mm and driving speed of 0.2 mm/s. The analysis of roughness was separated into two parts, including roughness profile, arithmetical mean deviation (Ra), and mean width of the profile elements (RSm). The process of measurement and analysis of roughness was controlled by JIS B0601 (2001) [25].

2.4. Full width at half maximum and residual stress analysis

X-ray diffraction (XRD) by Rigaku AutoMate Micro-area X-ray residual stress measurement system with Co-Kα radiation at 40 kV and 40 mA was used to measure the full width at half maximum (FWHM) and residual stress. FWHM was measured by the scanning angle range between 145° to 165° on its highest peak. Residual stress was specified by the fixed incidence angle method and calculated by the "$\sin^2 \Psi$" method [26,

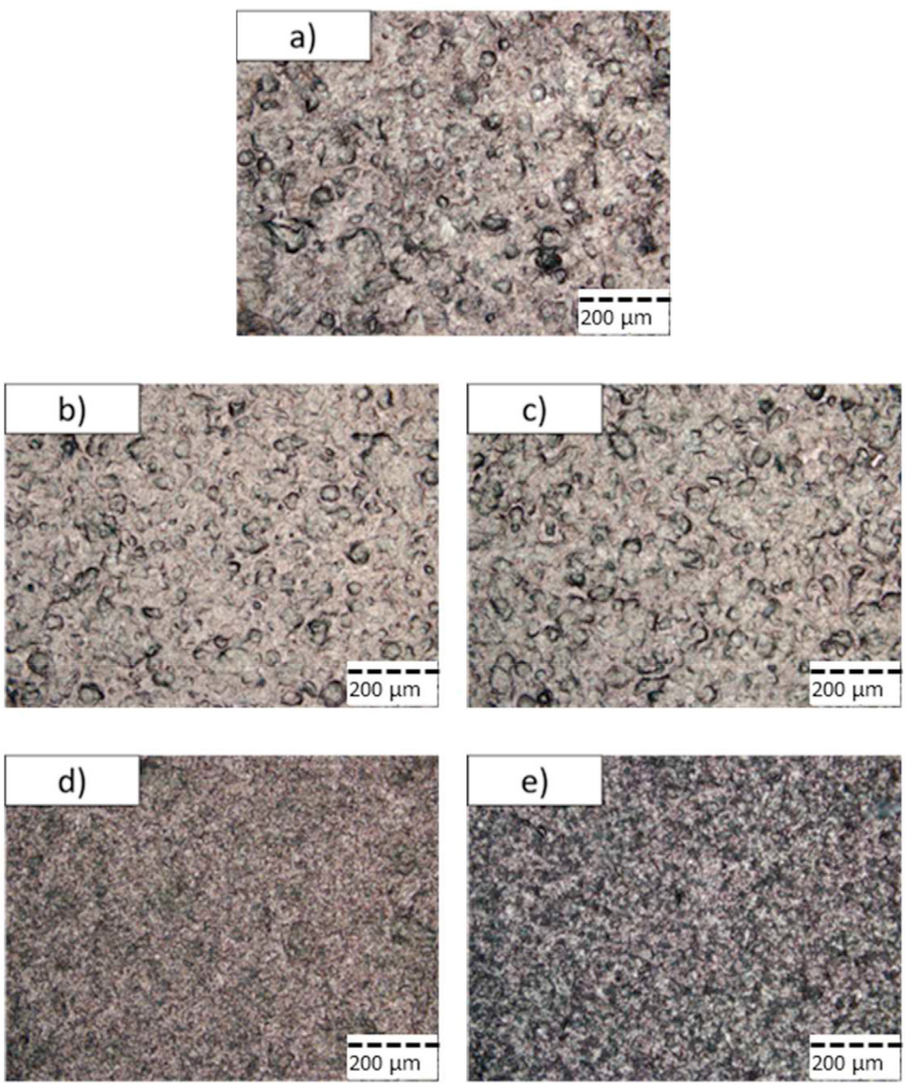

Figure 1. Surface morphology of the Ti–6Al–4V surface with different surface treatments. a) SP SUS400; b) DSUS50; c) DSUS100; d) DSi40; e) DSi80.

27]. The measurement method started from moving the detector from 0° to 45° to vary the psi angle (Ψ) and then having the diffraction angle (θ) measured. The calculation method used contact stress at -185.7 MPa and the slope of the $\sin^2 \Psi$ vs θ graph to calculate residual stress. Electro polishing was selected as the method to drill the surface from 0 μm to 60 μm for measuring FWHM and residual stress at different depths.

2.5. Hardness analysis

Shimadzu HMV-G Micro Vickers hardness was presented to measure the hardness of the material after the shot peening and double shot peening processes. The standard and calculation were controlled by ASTM E92 [28]. The points of measurement were classified into two parts, including the top surface to measure hardness on the surface, and cross-section to measure hardness in-depth from the surface. On the surface, 1.961 N of force and 10 s of holding time were employed, while cutting and polishing by sandpaper from 300 to 1500 grit were used to prepare for the measurement of hardness in-depth from the surface, whereby 245.2 mN of force and 10 s of holding time were determined to measure hardness in-depth from the surface. Hardness in cross-section was assessed from 10 μm to 70 μm by measuring every 10 μm.

2.6. Element analysis on the surface

The Energy Dispersive X-ray Spectrometer (EDS) was selected to measure the residual element on the surface after the shot peening and double shot peening processes by Bruker xflash 6130 connected to Nova NanoSEM 450. The 15.0 kV of Bias voltage and 1000 times magnification were specified as conditions of measurement. Bruker Esprit 1.9 software was used to analyze residual elements as percentages after mapping elements on the surface.

3. Results and discussions

3.1. Surface morphology and roughness

Figure 1 shows the surface morphology of Ti–6Al–4V after shot peening in different conditions. The result of double shot peening was clearly different from the conventional shot peening that was used in the first shot of the double shot peening process. The double shot peening generated many small dimples over large dimples, which were generated from the first shot, leading to the plastic deformation of the second shot, which can change the properties of materials [3, 5, 29]. Considering the media with similar size for the second shot used in double shot peening, it appeared that the surface morphology after shooting with silica media as shown in Figure 1d,e did change in all surfaces to small dimples over big dimples, so the surface morphology was changed more clearly than when shooting with SUS304 media as shown in Figure 1b,c. The silica media seemed to clearly generate small dimples on big dimples, although SUS304 media has a higher Almen intensity value. The result could be explained by the hardness of the media of silica, which is higher than that of SUS304, resulting in greater impact energy transfer to the material

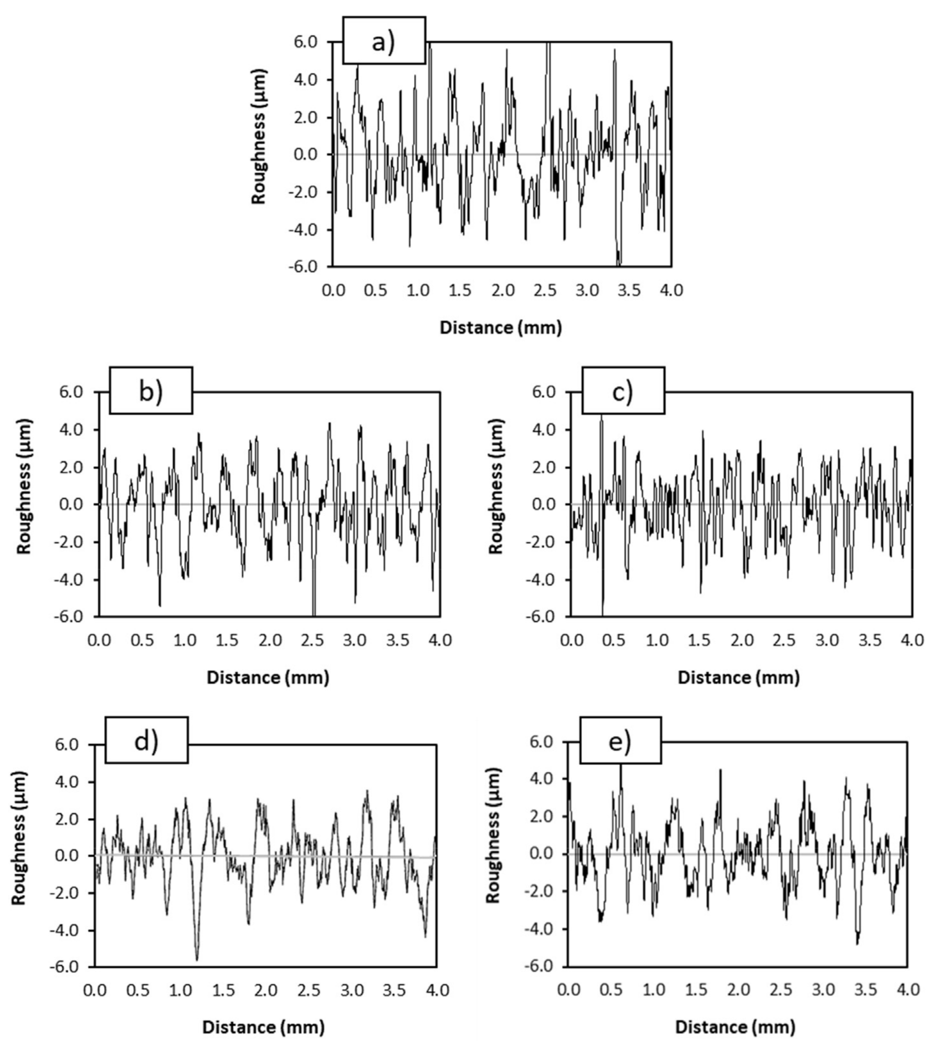

Figure 2. Surface roughness profile on the surface a) SP SUS400; b) DSUS50; c) DSUS100; d) DSi40; e) DSi80.

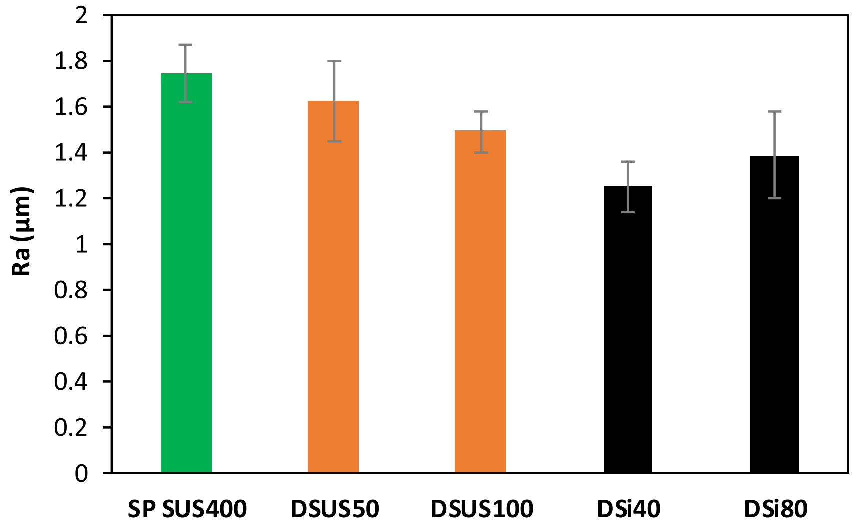

Figure 3. Arithmetical mean roughness on the surface with different shot peening conditions.

surface. The results also showed that the larger the size of the media, the bigger and clearer the dimples that were generated compared with those of smaller media due to the higher Almen intensity value. The higher change in surface morphology and the higher plastic deformation is affected by the hardness and residual compressive stress of Ti–6Al–4V. However, to study and observe more differences between each condition of double shot peening, a surface roughness test was conducted and is described in detail below.

The roughness profiles on the surface with different shot peening conditions are shown in Figure 2. The results showed that the roughness profile of double shot peening was lower in amplitude and different in frequency than conventional shot peening, which was used as the first shot of the double shot peening process. The change to a lower amplitude could be determined by the lower arithmetical mean deviation (Ra) as shown in Figure 3, while the change in frequency could be determined by the mean width of the profile elements (RSm) as shown in Figure 4. This could be described as the second shot of the double shot peening changing the shape of the large dimples obtained from the first shot by generating small dimples over the old surface, resulting in lower amplitude when compared with conventional shot peening [7]. The effect of different media types in the second shot on morphology was determined in this result. Both media were able to decrease the Ra value, which was decreased from 1.74 µm to 1.62 and 1.49 µm when double shot peening with 50 and 100 µm of SUS304 media respectively in the second shot, while double shot peening with 40 and 80 µm of silica media in the second shot would reduce the Ra value to 1.25 and 1.38 µm, respectively. However, it appeared that silica media exerted a more effective influence on decreasing the Ra value than SUS304 media, as silica media showed a greater capacity to create new dimples due to the higher hardness. This also aligned with the results of morphological change, which were discussed in the prior session. It is also stated that another significant point of roughness was the RSm value. Shooting silica media in the second shot would expand the dimples from the first shot, resulting in a changed RSm value from 0.2 mm of the first shot [7] to 0.24 and 0.22 mm by shooting with 40 and 80 µm of silica media respectively as the second shot. On the other hand, using SUS304 media in the second shot could shrink the dimples and reduce the RSm value from 0.2 mm to 0.18 and 0.16 mm by shooting with 50 and 100 µm of SUS304 media, respectively. It could be described that the higher Almen intensity, such as shooting with SUS304 media, would blunt the old peaks of the dimples from the first shot due to higher impact energy. Then, SUS304 media replaced them with small new dimples due to its low hardness, which could not generate full dimples, resulting in higher frequency of roughness compared to conventional shot peening. On the other hand, shooting with silica media,

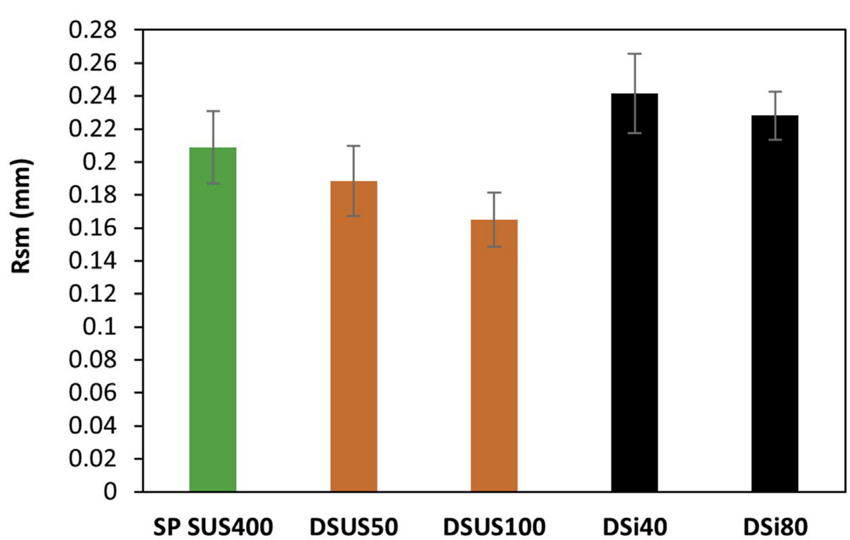

Figure 4. Mean width of the profile elements on the surface with different shot peening conditions.

which has a lower Almen intensity, could not blunt or deform the old peaks from the first shot, but due to its high hardness, silica media would generate new dimples over the peaks of the old dimples as shown in Figure 2, resulting in many small waves on top of the roughness peaks. Moreover, when increasing the media size in the second shot, the result showed that the bigger SUS304 media could generate lower Ra and RSm values because the bigger media size with higher Almen intensity is more effective in clearing the old peaks of dimples from the first shot. On the other hand, bigger silica media would increase the Ra value and decrease the RSm value. It can be described that as the media size of silica was increased, the dimples after shooting would be deeper due to higher Almen intensity, resulting in a higher Ra value than smaller media, while some of the old dimple shapes from the first shot were removed. From the above result, this could be considered as an effective way to increase the fatigue strength of Ti–6Al–4V because decreasing the roughness was able to decrease the stress concentration [30, 31]. Moreover, the changing of surface morphology and roughness determined the increase of residual compressive stress and hardness from plastic deformation [3, 7] that leads to an increase in crack resistance.

3.2. Full width at half maximum and residual stress analysis

Full width at half maximum (FWHM) is a value which is inversely proportional to domain size and related to the grain size of material following Scherrer's equation [21, 22]. In general, it is determined that FWHM of all surface treatments reveals higher values at the surface and gradually decreases at greater depths from the surface. For comparison, FWHM resulting from double shot peening was measured and compared with single shot peening [7], which were the conventional shot peening and fine shot peening that were used as the first shot and second shot in the double shot peening process. Figure 5 showed that there was no significant difference between conventional shot peening and double shot peening when using second shot media with low Almen intensity. It could be explained that after the first shot, the grain of the substrate material was broken and changed to a very small grain [32, 33, 34] and a huge amount of energy was required to break the grain into a much smaller size. Thus, when the energy of second shot media was low due to its low Almen intensity, the grain could not be deformed through this low energy. On the other hand, under the condition of double shot peening with SUS304 as the second shot media with a size of 100 μm, the higher value of FWHM at 0–20 μm depth from the surface could be determined. It could be cited that there must be sufficient energy to deform the grain of the material, resulting in a finer grain after the second shot in double shot peening with SUS304 as the secondary shot media. FWHM is a value that is related to hardness [22]. However, it was not described that there would be no changes in hardness of material after the double shot peening process although FWHM remained unchanged due to plastic deformation on the top surface while grain deformation could increase the hardness of the material. Nonetheless, at deeper levels from the surface where no effect of plastic deformation was found, the hardness of Ti–6Al–4V might not be changed as compared to the case of single shot peening because there was no change in the FWHM value obtained. This result corresponds with the hardness test results, which are to be discussed later.

On the other hand, residual compressive stresses were analyzed as shown in Figure 6. For comparison, residual compressive stresses obtained from both double shot peening and single shot peening, which was conventional shot peening and fine shot peening, were shown. Double shot peening was able to generate higher residual compressive stress at 0–10 μm from the surface or the area near the surface than conventional shot peening [7], which was used as the first shot of the double shot peening process. Moreover, double shot peening was able to generate the depth of residual compressive stress equivalent to single shot peening with large media named as conventional shot peening, which was deeper than single shot peening with smaller media named as fine shot peening [7], and used as the second shot in the double shot peening process. It could be described that using silica media in fine shot peening resulted in no effect over 40 μm from the surface, but only a less residual compressive stress over 60 μm from the surface by using SUS304 media, while double shot peening still obtained high values of residual compressive stress over 60 μm from the surface. According to the results for residual compressive stress of double shot peening, it could be said that double shot peening can produce high residual compressive stress on the surface, while retaining the depth profile of residual compressive

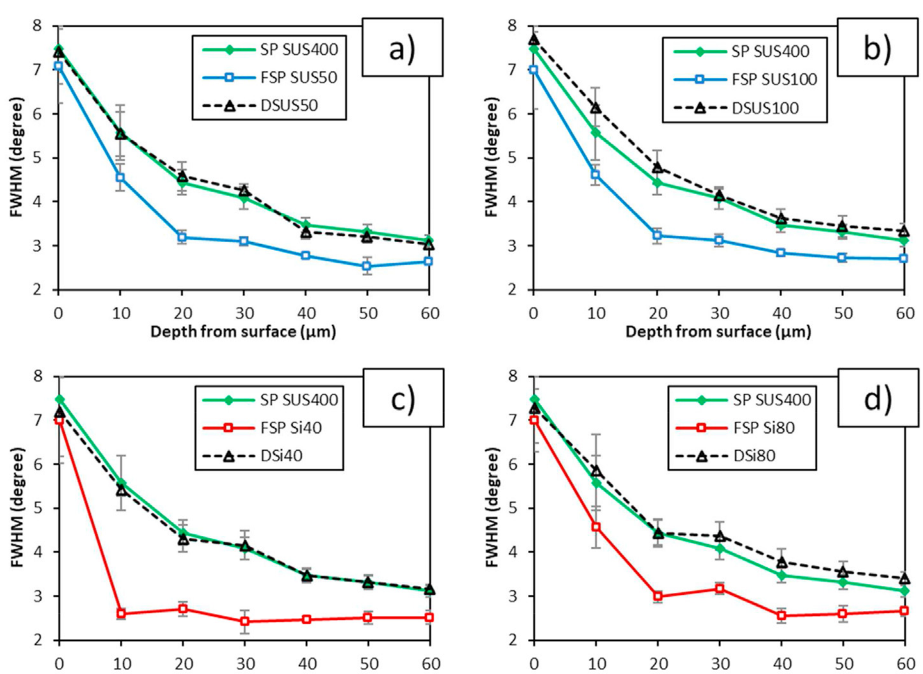

Figure 5. Full width at half maximum (FWHM) degree of Ti–6Al–4V at different depths from the surface compared between single shot peening and double shot peening a) DSUS50; b) DSUS100; c) DSi40; d) DSi80.

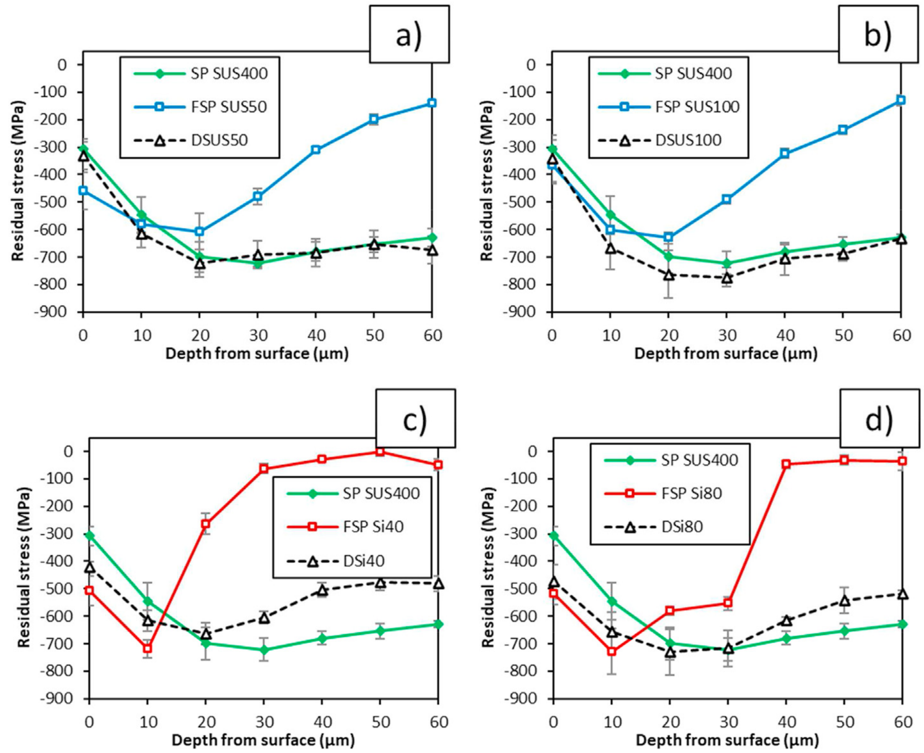

Figure 6. Residual stress of Ti–6Al–4V at different depths from the surface compared between single shot peening and double shot peening a) DSUS50; b) DSUS100; c) DSi40; d) DSi80.

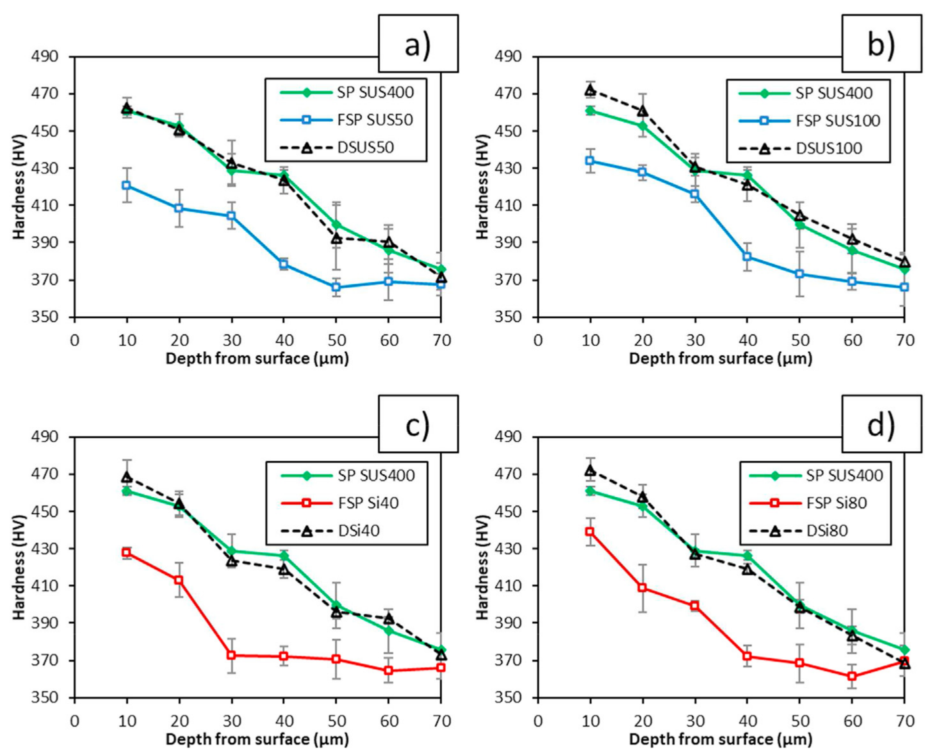

Figure 7. Hardness of Ti–6Al–4V at different depths from the surface compared between single shot peening and double shot peening a) DSUS50; b) DSUS100; c) DSi40; d) DSi80.

stress, which is fitted to tensile stress from the bending stress diagram. It could be further explained that after the first shot with high impact energy, residual compressive stress was created in the deep position, but with a lesser value near the surface. Then, after re-shot peening with the second shot by smaller media, which was able to generate a high value of residual compressive stress near the surface, the result showed that residual compressive stress was increased on the surface, while the depth effect was still confirmed. Nonetheless, after 30 μm from surface, it also seemed that residual compressive stress obtained from double shot peening with silica media as the second shot was lower than conventional shot peening. The result could confirm that after severe plastic deformation from silica media, the material tended to recover its deformation near the surface, which caused then introduction of small tensile stress at the in-depth position, resulting in less compressive stress. In the case of comparison between different media types of double shot peening, the result of shooting with 50 and 100 μm of SUS304 media as a second shot showed that at the surface, -387 and -348 MPa of residual compressive stress, respectively, could be confirmed, which was higher than the -308 MPa of conventional shot peening, while shooting with 40 and 80 μm of silica media generated higher values, which were -420 and -474 MPa respectively. The hardness of the media was determined as a cause for the changing of the residual compressive stress on the surface. Since silica media has higher hardness than SUS304 media, the impact energy transfer should be greater, resulting in higher plastic deformation on the surface, which affects residual compressive stress [32, 33, 34]. However, the maximum residual compressive stress value of double shot peening with SUS304 media as a second shot was higher than for silica media. Double shot peening with 50 and 100 μm of SUS304 media in the second shot created the highest residual compressive stress up to -724 and -763 MPa respectively, while 40 and 80 μm of silica media generated maximum values of only -661 and -730 MPa respectively. This could be further explained by the position of the maximum value as shown in Figure 6. After conventional shot peening, the position of the maximum residual compressive stress was around 20–30 μm from surface, which was almost the same as fine shot peening of SUS304 media at 10–20 μm, resulting in a combination of maximum residual compressive stress between the first shot and the second shot when conducting conventional shot peening as a first shot and fine shot peening as a second shot in the double shot peening process. It was noted that the position of the maximum residual compressive stress of single shot peening was dependent on Almen intensity, which affected impact energy [23, 24]. By increasing the media size of the second shot in the double shot peening process, the results showed that the maximum value of residual compressive stress could be increased by more than those of smaller media in the second shot at the same position due to higher impact energy. On the basis of the higher residual compressive stress at the surface and the depth effect from the surface after the double shot peening process, it is rational that double shot peening could generate higher bending fatigue strength in the material [5, 35, 36, 37].

3.3. Hardness analysis

The hardness of Ti–6Al–4V after different surface treatments obtained from different depths is shown in Figure 7. After the double shot peening process, a high level of hardness could be confirmed near the surface, which then gradually decreased with increasing depth from the surface. This result also showed that there was no significant difference in hardness at deep positions between double shot peening and single shot peening known as conventional shot peening [7], which was used as the first shot of the double shot peening process. This was assured from the FWHM results as shown in Figure 5, which affected hardness, that double shot peening and conventional shot peening were the same in the deep position. However, hardness at 10 μm from the surface generated from the large media of the second shot in double shot peening was quite different from conventional shot peening, while small media generated only a small difference from conventional shot peening. This result could be described as the changing of plastic deformation as the bigger media of the second shot had higher impact energy, which could be confirmed by the higher hardness from the bigger media of single shot peening, called fine shot peening, which was used as the second shot in the double shot peening process. From the higher hardness at 10 μm of Ti–6Al–4V obtained from double shot peening, it could be recognized that the hardness of the material after the double shot peening process was more greatly enhanced than under conventional shot peening near the surface to 10 μm. Regarding the comparison between SUS304 media and silica media in the second shot, the results showed that with the similar media size, silica media was able to generate higher hardness than SUS304 media. This could be explained by greater impact energy transfer from higher media hardness resulting in greater plastic deformation. According to the above results, in order to clarify the difference in hardness between double shot peening and single shot peening, including the effect of media parameters in the second shot, surface hardness was measured to explain further the results.

The surface hardness, which was measured on the top surface, showed that double shot peening was able to generate higher surface hardness than single shot peening [7] as shown in Figure 8, though the FWHM of double shot peening was stagnant. This could be defined by plastic deformation on the top surface, which was determined by surface morphology change as shown in Figure 1 and by surface roughness change as shown in Figure 2. The results also showed that hardness after double shot peening with 40 and 80 μm of silica media as the second shot was higher than 440 HV of conventional shot peening, which was used as the first shot of the double shot peening process, up to 477 and 502 HV, respectively, while SUS304 media generated lower hardness of 446 and 453 HV with media size of 50 and 100 μm. It could be explained that the higher hardness of silica media could be the cause of the result. The higher hardness media could generate greater impact energy transfer, which leads to greater plastic deformation. When increasing the media size of the second shot in double shot peening, the results showed that the bigger media size was able to generate higher hardness than was the case for the smaller media size. It could be described that when increasing the media size of the second shot in double shot peening, impact energy or Almen intensity would be also increased, resulting in huge plastic deformation of the material surface. From the above results, it could be defined that hardness after double shot peening was dependent on plastic deformation, which was generated by the second shot. Figure 8 shows the confirmation of the abovementioned results, as fine shot peening, which was used as the second shot in the double shot peening process, generated higher hardness. The increase in hardness by double shot peening was able to enhance fatigue strength of the material due to an increase in crack resistance [5, 38].

3.4. Element analysis on the surface

According to previous research [7], the results showed that there were some elements of media traces on the material surface, which could affect the biocompatibility properties [39, 40]. Therefore, this research also studied the residual elements on the surface to determine whether or not the media of the second shot would be able to stick on the surface in the manner of single shot peening, and whether elements of the first shot can be removed from the second shot or not. In this analysis, two conditions of double shot peening were selected: double shot peening with 80 μm of silica media and 100 μm of SUS304 media in the second shot. The results showed that after conventional shot peening, regarded as the first shot in the double shot peening process by SUS304 media, there were some Cr and Fe elements remaining on the material surface [7]. However, after double shot peening with 80 μm of silica media in the second shot, the results showed that Cr and Fe were reduced to 0.17% and 1.46%, while Si and O increased to 5.65% and 26.40% as shown in Table 3. Figure 9 shows the remaining Si and O over the surface obtained from mapping analysis. On the other hand, after shooting with 100 μm of SUS304 media in the second shot, the result showed that Fe increased to 11.8% (wt%), while a small decrease in Cr was determined. Figure 10 shows the mapping analysis of each major element on the surface after double shot peening with 100 μm of SUS304 media in the second shot. It appeared that SUS304 has been

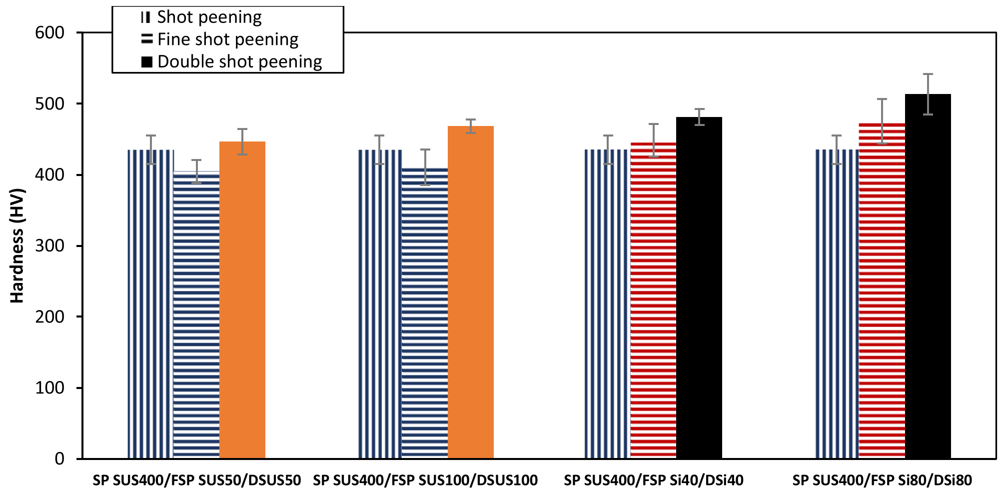

Figure 8. Hardness of Ti–6Al–4V on the top surface with different surface treatment conditions.

Table 3. Element analysis from EDS on the surface in wt%.

Code name	Si	O	Cr	Fe
SP SUS400 [7]	2.74	22.05	6.90	9.44
DSUS100	1.02	10.69	6.55	11.8
DSi80	5.65	26.40	0.17	1.46

attached on Ti–6Al–4V. However, since Fe and Cr increased after double shot peening with SUS304 media as the second shot, and reduced when using silica media as the second shot, it is possible that residual element of the second shot got stuck on the residual element of the first shot. The present study and analysis also indicate that there appears to be the remaining element of the first shot on the surface of Ti–6Al–4V after the double shot peening process, which means that the second shot in the double shot peening process is not able to clean or remove the layer of the first shot. As a result, the residual element should be further studied and examined towards usage of this application for medical devices, even though such elements are biocompatible and have not yet been the subject of reports about harmful effects.

4. Conclusion

This research focused on the effect of media types and media size of the second shot in the double shot peening process on residual compressive stress and hardness, which is considered significant for the improvement of bending strength of orthopedic devices. The conclusion is hereby shown as follows:

1. Double shot peening on Ti–6Al–4V is able to generate dimples over older dimples, which leads to the ability to reduce surface roughness. This process is also able to generate smooth residual compressive stress, which has a high value at the surface, the same as fine shot peening, and still the depth effect from the surface is found to be the same as conventional shot peening. Although, the FWHM value after double shot peening is not significantly different from the case of single shot peening, hardness after double shot peening increases to a greater extent than after single shot peening due to plastic deformation on the surface and residual elements on the surface.
2. Media type is considered to have a huge effect on generating smooth residual compressive stress and hardness. In this research, silica media is able to generate plastic deformation greater than SUS304,

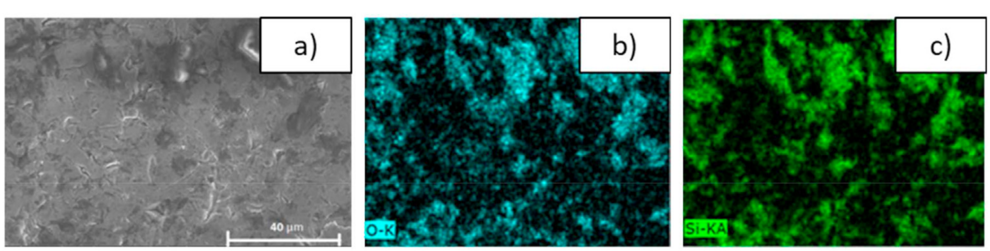

Figure 9. Mapping element of Si and O after double shot peening with DSi80 condition a) SEM image; b) O; c) Si.

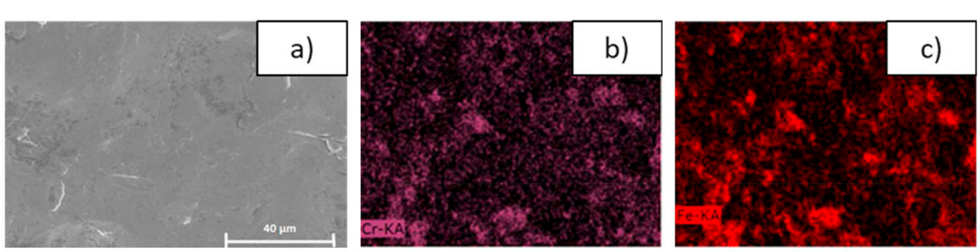

Figure 10. Mapping element of Cr and Fe after double shot peening with DSUS100 condition. a) SEM image; b) Cr; c) Fe.

resulting in significant change on the surface and a greater ability in reducing roughness. Moreover, silica media generates higher residual compressive stress and hardness near the surface than SUS304 media due to the hardness of the media, which is affected by impact energy transfer and residual elements. It is concluded that the media which is used in the second shot must be higher in hardness than the media of the first shot to generate high residual compressive stress and hardness at the surface. On the other hand, SUS304 media is able to increase hardness and residual compressive stress at the in-depth position to a greater extent than silica media due to the higher density of media that leads to a greater impact energy.

3. Media size also affects residual compressive stress and hardness due to the Almen intensity, which shows the impact energy of shot peening. The larger media of silica and SUS304 is able to generate higher values and deeper positions of residual compressive stress and hardness due to the higher Almen intensity. It is concluded that the media size used in the second shot should not be too small because the energy obtained from small media is not enough to generate plastic deformation on the surface and to change the properties of the materials.
4. In conclusion, the best solution of double shot peening to generate high residual compressive stress on the surface with the remaining depth effect from the surface is to use large media to provide huge impact energy in the first shot to produce residual compressive stress towards the in-depth effect of residual compressive stress. Then, the second shot media should be of high hardness with compatible size to generate high residual compressive stress on the surface and reduce roughness on the surface.

Declarations

Author contribution statement

Goratouch Ongtrakulkij, Anak Khantachawana, Julathep Kajornchaiyakul, Katsuyoshi Kondoh: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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