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Comparison of Surface Characteristics of Medical-grade 316L Stainless Steel Processed by Sand-blasting, Slag Ball-blasting and Shot-blasting Treatments

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Highlights:

- All blasting treatments with various blasting particles increased the roughness and hardness of the steel surface.
- The roughest stainless steel surface was achieved by the slag ball-blasting treatment, but shot-blasting produced the stainless steel with the hardest surface and the thickest hard subsurface layer.
- The physical properties and surface morphology of the particles or shot used in the blasting treatment are critical parameters in determining the surface characteristics of blasted stainless steel.

Abstract. In this research, a comparative study was carried out to examine the surface characteristics of medical-grade 316L stainless steel after blasting treatments by using angular silica particles, spherical slag balls and spherical metallic shot. The surface roughness, morphology, elemental composition and microhardness distribution of the stainless steel were determined and the possible mechanisms in the evolution of the surface characteristics of the steel exposed to the blasting treatments were established. The results showed that all the blasting treatments conducted in this research increased the roughness and hardness of the steel surface. In this case, the roughest stainless steel surface was achieved by the slag ball-blasting treatment, but the stainless steel with the hardest surface and the thickest hard subsurface layer was obtained by the shot-blasting treatment. On the basis of the findings in this research it can be concluded that the physical properties and surface morphology of particles or shot used in the blasting treatment are critical parameters in determining the surface characteristics of blasted stainless steel.

Keywords: *316L stainless steel; sand-blasting; shot-blasting; slag ball-blasting; surface characteristics.*

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1 Introduction

Surface morphology and roughness have so far been considered as among the most critically important parameters in determining the performance of metallic orthopaedic implants. For instance, the osseointegration of titanium-based implants is generally improved by increasing the surface roughness of the implant [1,2]. However, a highly rough surface layer potentially deteriorates the corrosion resistance [3,4] and fatigue strength [5] of metallic biomaterials and biomedical implants and also increases the susceptibility of such materials to bacterial adhesion [6]. Therefore, control of the surface morphology and roughness of metallic implants should be carried out throughout their manufacturing process to maintain their functionality and service lifetime.

In the last few decades, sand-blasting and shot-blasting have been widely used as post-processing treatments for improving the functionality and performance of metallic biomaterials and biomedical implants [1,3,7,8]. Several studies have demonstrated improved osseointegration of titanium implants owing to their rough surface as generated by sand-blasting [1,7]. Meanwhile, shot-blasting, also called shot-peening, has also been reported to be able to improve the fatigue resistance of metallic materials by generating a fine-grained structure on the surface and subsurface layers of the shot-blasted material [9].

Apart from being useful for improving the performance of metallic implants, sand-blasting and shot-blasting have also received attention from researchers because of their application in the post-processing of low-cost and biocompatible 316L stainless steel. In recent studies, the surface morphology and roughness of 316L stainless steel series were varied with the duration of the blasting treatment [10-12]. As was shown in previous studies, a rough metallic surface can be produced by blasting of angular, irregularly shaped particles [10,13,14] instead of smooth and spherical shot [12]. However, the influence of the blasting particles or shot on the resulting surface characteristics of medical-grade 316L stainless steel has not been explored yet.

In this research, a comparative study was carried out to examine the surface characteristics of medical-grade 316L stainless steel after blasting with angular silica particles, spherical slag balls and spherical steel shot. Surface characterizations were conducted following the blasting treatments to determine the surface roughness, morphology and elemental composition of the blasted stainless steel specimens. Meanwhile, the subsurface microhardness distribution was also investigated to confirm the microstructural changes that occurred in the blasted material resulting from the treatments. Finally, the mechanisms operating in the evolution of the surface characteristics of the blasted steel are proposed.

2 Materials and Methods

2.1 Materials Preparation and the Blasting Treatment

In this research, three groups of specimens were prepared from a medical grade 316L stainless steel plate with dimensions of 15 mm × 15 mm × 4 mm and a chemical composition (wt%) of 0.03 C, 16.69 Cr, 10.57 Ni, 2.39 Mo, 1.74 Mn, 0.67 Si, 0.34 Cu, and balanced Fe. Prior to the blasting treatments, the specimens were first ground and polished using a set of abrasive sandpapers to obtain specimens with a uniform surface roughness. The blasting treatments were then carried out with a duration from 0 to 20 min in a custom-built grit blasting unit, as specified in [11]. In this study, the specimens were subjected to three blasting treatments: (1) with silica particles, (2) with slag balls and (3) with metallic shot as the blasting media. The physical properties of each blasting material are presented in Table 1.

Table 1 Physical properties of the blasting media used in this research.

Parameters	Silica particles	Slag balls	Metallic shot
Shape	Angular, non-spherical	Nearly spherical	Spherical
Density (g cm^{-3})	2.19	3.67	7.65
Size (mm)	~0.2	2 – 5	3.2
Compounds over the surface of the blasting media*	C, Al, Si, Ca, Zr	C, Mg, Al, Si, Ca, V, Fe	Al, Si, Fe

* As detected by using energy dispersive X-ray spectroscopy (EDS)

2.2 Surface Characterization and Microhardness Measurement

After the blasting treatments, the surface of the blasted specimens was cleaned with 70% ethanol and then characterized using an electron microscope (JSM-6510LV, JEOL Ltd., Japan) to examine their morphologies and elemental compositions. Meanwhile, the surface roughness was determined by using a contact stylus profilometer (Surfcom 120A, Advanced Metrology System, UK) over five different locations on the surface of each specimen. Finally, the microhardness distribution was determined by using a microhardness tester with a Vickers indenter (Buehler, USA). This measurement was conducted in triplicate with an indentation load of 4.9 N that was held for 15 s over the polished surface of each specimen's cross-sectional area.

3 Results and Discussion

In this research, the use of three types of blasting particles, namely silica particles and slag balls, and spherical metallic shot were evaluated in terms of their ability to modify the surface characteristics of medical-grade 316L stainless steel through blasting. Silica particles have long been recognized as suitable particles for sand-blasting treatment of metallic materials, including those for biomedical applications [10,14]. Similarly, the use spherical metallic shot for the surface treatment of metallic biomaterials has also been reported [12,15]. Meanwhile, the use of waste particulate materials such as slag balls in blasting treatments has only recently been reported [11].

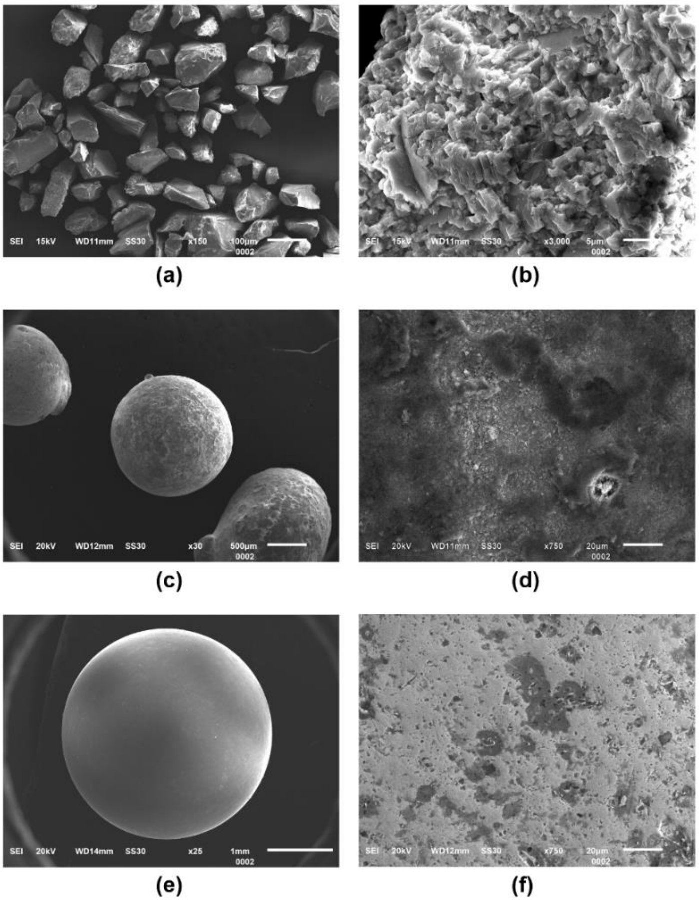


Figure 1 The shapes and morphologies of the particles and shot used in the blasting treatments: (a) angular silica particles, (b) surface morphology of the angular silica particles, (c) steel slag ball, (d) surface morphology of steel slag ball, (e) spherical shot, and (f) surface morphology of spherical shot.

Figure 1 shows the shapes and surface morphologies of all the blasting particles and shot used in this research. Obviously, the silica particles were angular and had an irregular surface morphology, as shown in Figure 1(a) and (b). In contrast, the metallic shot was spherical and had a relatively smoother surface than both the silica particles and the slag balls, as can be seen in Figures 1(e) and (f). Meanwhile, the slag balls were nearly spherical but had an irregular surface morphology, as shown in Figure 1(c) and (d).

Figure 2 demonstrates the roughness evolution of the blasted stainless steel surface that occurred during the blasting treatments with silica particles, slag balls and metallic shot. In this figure, the surface roughness of the specimens is presented quantitatively in the form of the average arithmetic medium value (*Ra*) of five randomly selected locations on the surface of each specimen. In general, the roughness evolution of the stainless steel surface during the blasting treatments consisted of three stages, i.e. (i) surface roughening, (ii) roughness decreasing, and (iii) saturation. A similar pattern of roughness evolution could be seen during the surface mechanical attrition treatment (SMAT) of the stainless steel [15]. In Stage I, surface roughening occurred during the first couple of minutes of the blasting treatment as a result of the formation of new dimples and pile-ups on the specimen's surface. In Stage II, the *Ra* value of the specimens decreased as all the locations on the specimen's surface had been impacted by the blasting particles or shot, sometimes even multiple times. Finally, Stage III was reached when the specimen surface roughness was apparently no longer altered when the blasting treatment was continued. It was clearly shown in this study that the blasting treatment with slag balls yielded the steel surface with the highest *Ra* value over the entire duration of the blasting treatment, i.e. 2.5 to 3.5 μm. Meanwhile, the specimen with the lowest *Ra* value, i.e. 1 to 1.5 μm, resulted when spherical metallic shot was used as the blasting media.

Based on the standard deviations, which are presented as error bars over the mean *Ra* values in Figure 2, sand blasting with silica particles and slag ball-blasting apparently yielded stainless steel with similar roughness, where the roughness of the steel surface, i.e. $Ra = 2.5$ to 3.5 μm, was twice as high as that of the shot-blasted steel surface, $Ra = 1.0$ to 1.5 μm.

The results presented in Figure 2 are confirmed by the series of micrographs in Figure 3, which obviously show the changes in the surface morphology of the specimens after 15 min of all blasting treatments. The surface of the polished control specimen was apparently smooth, although some minor scratches can still be seen in Figure 3(a), which resulted from the mechanical polishing conducted during specimen preparation. Meanwhile, the micrographs of both specimen surfaces that were blasted by using silica particles and slag balls showed irregular surface morphologies, revealing some protrusions, defects and cracks over the specimen surface (Figure 3(b) and (c), respectively). Meanwhile, the micrograph in Figure 3(d) shows the surface morphology of the shot-blasted specimen, revealing a more regular surface structure than the surfaces processed using silica particles and slag balls in Figure 3(b) and (c), respectively. On the shot-blasted surface some small pits spread over the entire surface layer can be observed.

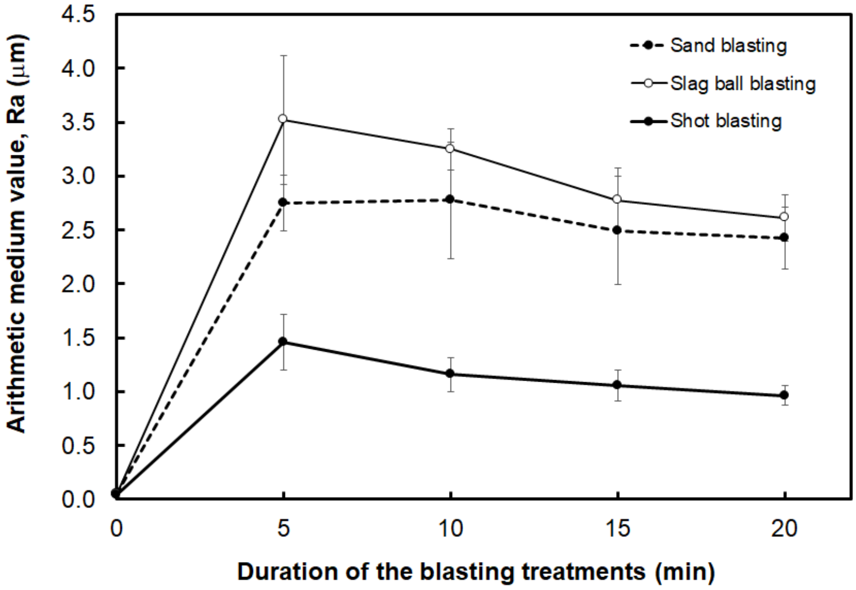
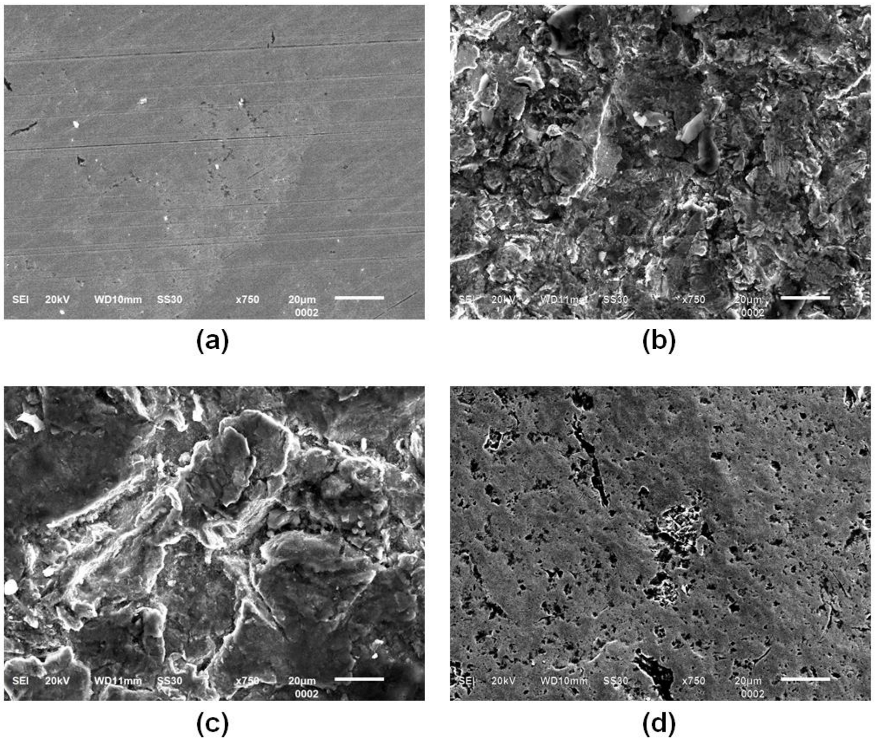


Figure 2 Surface roughness evolutions of 316L stainless steel during the sand-blasting, slag ball-blasting and shot-blasting treatments.

All these features correspond to deep valleys and surface damage due to multiple high-energy impacts of the blasting shot. These findings confirm that the surface morphology after blasting particles or shot is among the critically important parameters in determining the morphology and roughness of the resulting blasted surface. Instead of causing severe surface erosion and damage, the impacts of the smooth and spherically-shaped metallic shot deformed the blasted material and produced a surface with lower *Ra* values than the angular and less-spherically shaped silica particles and slag balls during blasting. As also noted previously, blasting particles with angular shapes cause surface material loss or erosion by a cutting mechanism when impacting the blasted surface [16,17]. In agreement with these previous reports, the irregular surface morphology and sharp edges of both the silica particles and the slag balls indented, gouged and even removed some of the surface material [11], which ultimately led to the formation of a rough surface layer.



(a) (b)

(c) (d)

Figure 3 Surface morphologies of 316L stainless steel (a) before blasting and after blasting for 15 min using (b) silica particles, (c) slag balls and (d) spherical metallic shot.

The microhardness distributions across the specimens' sectional area are demonstrated in Figure 4. As can be seen in this figure, all the blasting treatments were able to increase the hardness of the surface and subsurface layers of the specimen. This finding confirmed the results obtained in previous works with other mechanical surface treatments [10-13,15]. Interestingly, the shot-blasting treatment conducted in this research was able to produce the specimen with the hardest surface and subsurface layers. Meanwhile, both the sand-blasting and slag ball-blasting treatments produced specimens with similar hardness distributions.

Surface and subsurface hardening of stainless steel due to blasting treatments has been widely reported in the literature [13,18,19]. In principle, the increased hardness of the surface and subsurface layers of the blasted material can be attributed to work hardening, which can result in the formation of martensite, a fine-grained structure and residual stress on these layers after receiving multiple impacts from the blasting media [13,19].

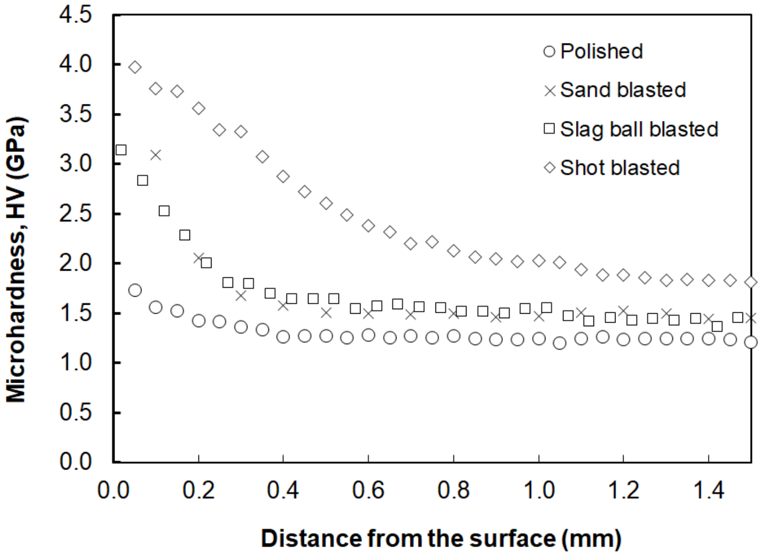


Figure 4 Microhardness distribution across the sectional area of the 316L stainless steel after blasting for 20 min.

As has been noted previously [15], the magnitude of the impact force delivered by the blasting particles or shot determines the level of deformation and microstructural change of these layers. To aid in describing this phenomenon, Eq. (1) is presented, which can be used for estimating the magnitude of the impact force (F) generated during the impact of a single blasting particle or shot towards the blasted surface of a material:

$$F = m\,(v' - v_0) / dt \tag{1}$$

where m and dt are the mass of a single blasting particle or shot and the time during which such a blasting particle or shot is in contact with the blasted surface once impact occurs, respectively. Meanwhile, v_0 and v' are the velocities of the blasting material prior to and during contact with the blasted surface during treatment, respectively. In this case, v' equals zero as the blasted specimen was statically fixed on the sample holder of the blasting unit. Both v_0 and dt are actually difficult to determine, as they involve several factors that should be considered appropriately prior to and during the impact of the blasting particles or shot against the surface of the blasted specimen. Therefore, both v' and dt of all the blasting media used in this research were assumed to be the same. By using Eq. (1) and considering the abovementioned assumption, it is only the mass of the blasting particle or shot that determines the magnitude of the impact force. Therefore, it was confirmed that a greater mass of the spherical metallic shot compared to the silica particles and the slag balls (see Table 1) is able to deliver a greater impact force, producing a specimen with a harder surface and harder subsurface layers.

Al-Obaid [20] has given the correlation between the shot-peening parameters and the formed plastic region that corresponds to the surface and hard subsurface layers of the blasted material in Eq. (2):

$$\frac{h_p}{R} = 3\left(\frac{2}{3}\right)^{1/4}\left(\frac{\rho V_0}{\bar{p}}\right)^{1/4} \tag{2}$$

where h_p and R are the depth of the plastic zone and the shot radius, ρ and V_0 are the density and the impact velocity of the shot, and $\bar{p}$ is the average pressure that resists the motion of the shot when indenting the treated surface. By assuming that $\bar{p}$ remains constant during the indentation process, Eq. (2) confirms the finding in this study that a thicker surface and thicker hard subsurface layers can be formed by shot-blasting, considering the greater density of the shots than by using silica particles or slag balls in the blasting treatment.

Table 2 Chemical elements on the surface of 316L stainless steel after blasting treatment for 15 min characterized using EDS.

Elements	**Percentage mass of the elements (%)**			
	Polished, control surface	**Sand-blasted surface**	**Slag ball-blasted surface**	**Shot-blasted surface**
Fe	52.83	37.49	31.97	52.55
Cr	13.50	9.78	7.54	13.48
Ni	7.42	5.08	3.31	7.32
Mo	1.91	-	-	1.58
C	-	9.21	20.37	-
Al	-	1.10	1.04	-
Si	-	7.84	1.60	0.47
Ca	-	0.70	11.60	-
Mg	-	-	0.99	-
O	24.34	27.49	21.58	24.60

Finally, Table 2 shows the compositions of the elements in the surface layer of the stainless steel as detected by energy dispersive X-ray spectroscopy (EDS). With EDS, the surface contamination of the blasted specimen due to the blasting treatment could be determined by comparing the elements that were present in its surface layer with the elements of the blasting particles used in the treatment [14]. As can be seen in Table 2, several elements of the silica particles and slag balls were detected in the blasted steel surface layer, for example C, Al, Si, Ca and Mg, in addition to the building elements of stainless steel itself, such as Fe, Ni and Cr. This finding confirms the result reported in previous studies [7,13,14]. The introduction of such contaminants can be attributed to small fragments of the blasting particles or shot that are formed during impact with the blasted specimen surface. During impact, the high kinetic energy of the blasting particle or shot may be able to break these materials apart into many small fragments. Such irregularly shaped, even sharp-edged small fragments are then embedded and are difficult to observe visually. They can be removed by using the cleaning procedure used in this research. Meanwhile, only Si could be observed as a contaminant on the surface of the shot-blasted specimen, indicating a higher integrity of the shot material when impacting the surface of the specimen. To conclude the findings obtained in this research, Figure 5 shows a series of schematic illustrations describing the possible mechanisms in the surface evolution of the medical-grade 316L stainless steel that occurred during the blasting treatments using silica particles, slag balls and spherical metallic shot.

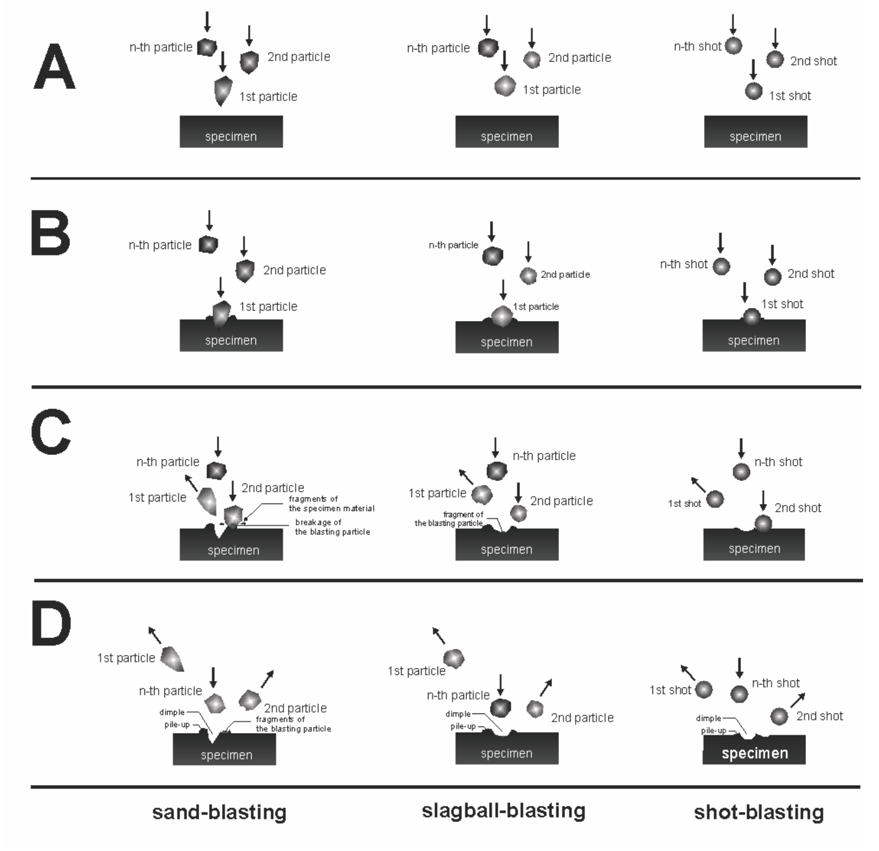


Figure 5 Schematic illustrations of the mechanisms in the surface evolution that occurred in the metallic material during the blasting treatments conducted in this research.

As can be seen in Figure 5(a), all the particles and shot initially flew towards the smooth specimen surface with velocity v_0. Once impacted by the first blasting particle or shot, the blasted surface was deformed, forming a dimple or crater in this layer, as shown in Figure 5(b). In addition, pile-ups were formed surrounding the crater or dimple, contributing to increased surface irregularity. It is also important to note from Figure 5(b) that the impact of the blasting particles or shot induced microstructural changes and generated residual stress on the surface and subsurface layers of the blasted material, which is confirmed above by the increased hardness of these layers, as shown in Figure 4.

The impact of the subsequent blasting particles or shot towards the surface layer and pile-ups may be able to detach some material from this layer in the form of small fragments, as shown Figure 5(c). Meanwhile, the high-energy impact of a blasting particle or shot is also be able to break the elements of the particle or shot apart. This phenomenon was evident in the case of sand blasting with silica particles and blasting with slag balls, where the elements of these blasting particles could be found in the form of small fragments of these particles over the blasted stainless steel surface. In the end of the impact sequence, a rough surface was obtained and the blasting particles or shots bounced off from the blasted surface, as can be seen in Figure 5(d).

4 Conclusions

In this research, a comparative study was carried out to examine the surface characteristics of medical-grade 316L stainless steel after blasting using angular silica particles, spherical slag balls and spherical steel shot. On the basis of the results obtained in this research, the surface characteristics of the blasted 316L stainless steel were determined by the physical properties of the blasting particles and shot used in the treatments, i.e. shape, morphology, and density. Therefore, it can be concluded that the physical properties of the blasting particles or shot are among the critically important parameters in determining the morphology, roughness and hardness of the resulting blasted surface. By considering these findings, the appropriate blasting media can be selected to achieve a metallic material with the desired surface characteristics.

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