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Effect of shot peening on microstructure, hardness, and corrosion resistance of AISI 316L

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ABSTRACT

Purpose: This research conducted to analyse the effect of shot peening on surface structure, hardness, and resistance to corrosion of AISI 316L.

Design/methodology/approach: The shot peening process is carried out on the surface of 316L stainless steel samples with four peening durations, and they are 2, 4, 15, and 30 minutes. Shot ball steel with diameter 0.4 mm for metal shot blasting and model S110 of ISO 11124/3 and SAEJ827, with the chemical composition, are C (0.8-1.2 wt.%), Mn (0.6-1.2 wt.%), Si (min. 0.4 wt.%), S (max. 0.05 wt.%), P (max. 0.05 wt.%), with a hardness of steel-ball, about 40-50 HRC. The pressure of compressor kept constant at 8 bar with a diameter of the nozzle is 5 mm, and the distance between the nozzle and the sample surface variated by 6 cm and 12 cm for each shooting duration.

Findings: The result shows that the shot peening increases the surface hardness of the material, changes the microstructure on the surface layer and increases the resistance to corrosion. Shot peening with 30 minutes of shooting duration and 6 cm of shooting distance can improve the metal surface properties, which has a surface hardness of 772.23 HV and good on corrosion resistance.

Research limitations/implications: The results of this experiment show that shot peening distance of 6 cm for 30 minutes achieved the highest surface hardness of AISI 316L. The corrosion rate decline with increasing duration and nearer distance of shooting balls.

Practical implications: In the development of the implant material, AISI 316L need to be improved, its material properties, so it can be used safely and compatibly. Shot peening is a cold working process of metal to increase the material properties by shooting the steel ball into the surface of a material.

Originality/value: Based on the experimental results it was obtained that variations shot peening distance and shot peening duration can change grain morphologies, subsequently affect hardness and corrosion resistance on AISI 316L.

Keywords: Shot peening duration, Shot peening distance, 316L stainless steel, Surface hardness, Microstructure, Corrosion

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PROPERTIES

1. Introduction

AISI 316 L is widely used as an implantable material, to make artificial joints, bone plates, stents, prostheses, because this material is one type of stainless steel, has good mechanical properties and relatively cheaper than other metallic biomaterials [1]. Several studies have shown that AISI 316 L has better mechanical and corrosion resistance properties than AISI 304 [2]. However, there is a need for improved quality and corrosion resistance to obtain material that is safe and resistant to dynamic loads in bone implants.

There are several techniques for improving the physical and mechanical properties of materials by engineering the properties of the steel and its alloys. This technique is carried out by a surface treatment process which is generally intended to obtain certain properties of surface materials such as fatigue [3-7], microhardness, yield strength, tensile strength [5], corrosion resistance [2,8,9], wear resistance [10], residual stress [6,8,11-13], wettability [13], roughness [8,14]. The process of shot peening and sandblasting is one method of surface treatment to improve the mechanical properties of materials.

The shot peening process is a process that is performed by shooting high-speed steel balls on the surface of the specimen in order to give a compressive residual stress on the surface of a component that can improve the material properties to the dynamic load. The shot peening process will make the metal surface becomes rougher and flatter, plastic deformation, strain hardening, sealing the porosity, increasing the resistance to compressive residual stress on the surface of the material, which will enhance the mechanical properties of material [3,15].

The objective of this experiment is to observe on the effect of shot peening treatment with the variation of 6 cm and 12 cm shooting distance and shooting duration of 2, 4, 15, and 30 minutes at each distance, on microstructure, hardness, and resistance to corrosion of AISI 316L.

2. Material and methods

The 3 mm SS 316 L specimens were cut into 37.5 x 20 mm sizes of 8 specimens. The plate is then smoothed with abrasive paper that has been set to gradually mesh size 100-5000 and polished with autosol.

The shot peening apparatus developed in our laboratory. A 3HP 120L 10 Bar 380V compressor used with a nozzle diameter of a 5 mm. Shot ball steel with diameter 0.4 mm for metal shot blasting and model S110 of ISO 11124/3 and SAEJ827, with the chemical composition, are C (0.8-1.2 wt.%), Mn (0.6-1.2 wt.%), Si (min. 0.4 wt.%), S (max. 0.05 wt.%), P (max. 0.05 wt.%), with a hardness of steel-ball, about 40-50 HRC. The specimens treated with some variations, they are two distances between the nozzle and the sample surface (6 and 12 cm), and four durations of the peening process (2, 4, 15, and 30 minutes). The pressure of compressor kept in constant at 8 bar during the shot peening process.

Microstructure testing was performed to identify the effect of shot peening visually. The specimen performed by the microstructure testing is a specimen of shot peening treatment that has been cross-cut and seen in its cross section. The cross-section is smoothed first using sandpaper gradually with mesh 100-5000 and polishing with autosol. After shiny, the specimen is then etched using a mixture of HCl with HNO_3 for 40 seconds. The function of etch is to make disappear the oxidation layer on the surface of specimens. Then the specimen was observed with a microscope with magnification 100 times so it can be analysed the effect of the shot peening treatment on the specimen.

Surface hardness testing was performed using the Micro Vickers tool named Buchler Micromet 2100 series. The surface hardness test uses an indentation load of 100 gf for about 10 seconds. The indentation was performed 7 times on each specimen, then calculated to obtain an average of VHN (Vickers Hardness Number). Vickers hardness values can be obtained by Equation (1):

$$VHN = \frac{2.P.\sin\left(\frac{\theta}{2}\right)}{d^2} = 1.854\left(\frac{P}{d^2}\right) \qquad (1)$$

where : VHN = Vickers Hardness Number,
P = applied load (kg),
D = average diagonal of indentor (mm),
θ = diamond pyramid angle (136^o).

Corrosion rate testing is done using Ametek Versatat 4. Corrosive media used is infusion which is similar to human body fluid. Corrosion testing was performed on raw material (non-treatment/NT) and shot peening specimens of AISI 316L were cut into cylinders of 14 mm in diameter. In this research, a cycle polarization method is used to determine the possibility of pitting corrosion. The corrosion rate can be determined based on the resulting I_{corr} value. The resulting data is the plot between the potential with the amount of current that occurs. The corrosion rate of a metal in the environment is proportional to the value of the density of the corrosion current.

Corrosion test solution used in this experiment was Otsu-Ns infusion solution with the crystalloid solution is 0.9% sodium chloride, its tested at room temperature. The composition of the infusion solution is electrolytes (sodium, calcium, potassium), nutrients (usually glucose), vitamins. In the medical field, the infusion solution usually gives to patients for replacing body fluids containing water, electrolytes, vitamins, proteins, fats, and calories, improving acid-alkali balance, improving the volume of blood components, and also monitoring central venous pressure (CVP). As with the following corrosion rate Equations (2):

$$r = 0.129 \frac{a.i}{n.D} (mpy) \tag{2}$$

where: r = corrosion rate (mpy),
a = atomic mass number,
i = corrosion current density ($\mu A/cm^2$),
n = atomic valence,
D = specific weight (g/cm^3).

To calculate the corrosion rate of the alloying material, it must be calculated first the value of Equivalent Weight (EW) using the following Equations (3,4):

$$EW = N_{EQ^{-1}} \tag{3}$$

$$N_{EQ} = \sum \left[\frac{\omega_i}{a_i / n_i} \right] = \sum \left[\frac{\omega_i n_i}{a_i} \right] \tag{4}$$

where: EW = equivalent weight,
N_{EQ} = total of equivalent weight,
ω_i = weight fraction,
a_i = atomic mass number,
n_i = valence electron.

Thus, the corrosion rate Equation (5) for alloying materials becomes:

$$r = 0.129 \frac{i_{corr}(EW)}{n} (mpy) \tag{5}$$

where: r = corrosion rate (mpy),
EW = equivalent weight,
D = specific weight (g/cm^3).

3. Results and discussions

3.1. Microstructure

The microstructure test results are photographs of microstructure from the surface of the material taken using an optical microscope with 100 times magnification. Qualitative image analysis to measure particle size in a microstructure was analysed using the linear intercept method. Micrograph data are representative of points 8-10 randomly, with an area of 120.128 μm^2 to be analysed [16].

The grain size of non-treatment AISI 316L material was 34.22 µm. The grain size measured on the near-surface area with a depth of about 10-30 µm and in the more deeper area that measured about 150-170 µm, as shown in Figure 1. Grain size on the near surface-sample with 6 minutes duration of shot peening ranged from 15-29 µm. The grain sizes are smaller when compared to the more deeper area which ranges from 30-40 µm with 6 minutes of shot peening duration. For 12 minutes of shot peening, the grain sizes on the near-surface zone are around 14-28 µm and in the more deeper area around 31-38 µm.

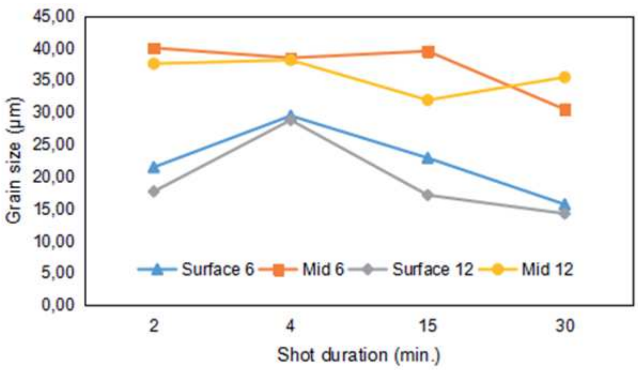

Fig. 1. Average grain size of the AISI 316L as a function of shot peening duration on a surface and in the middle

Figures 2 and 3 show the microstructure with large grains structural on the NT material. After the material is treated by shot peening, the grain structure is seen having to smooth the area around the surface of the material, then the grain structure show bigger, with more and more distant from the surface. Figures 2 and 3 provide information that the duration of shot peening also affects the microstructure of the material, i.e. the longer the duration of the shoot, the grain boundary between the small grain and the larger grain farther from the surface. Distance shooting also gives effect to the microstructure of a specimen shot peening. It will be seen on specimens with a 6 cm distance of shot having grain boundaries farther from the surface compared to specimens with a 12 cm distance of the shot. This is because the shooting intensity that occurs at a distance of 6 cm is certainly greater than at a distance of 12 cm.

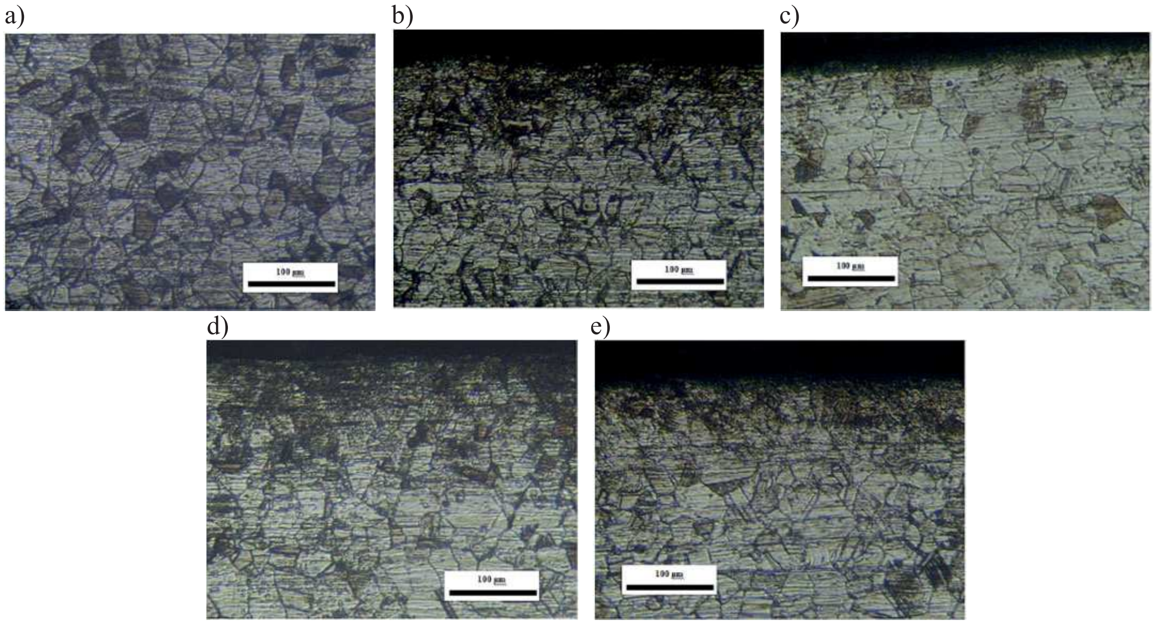

Fig. 2. The microstructure of the shot peening material with a shooting distance of 6 cm: a) NT material, b) 2 minutes, c) 4 minutes, d) 15 minutes, e) 30 minutes

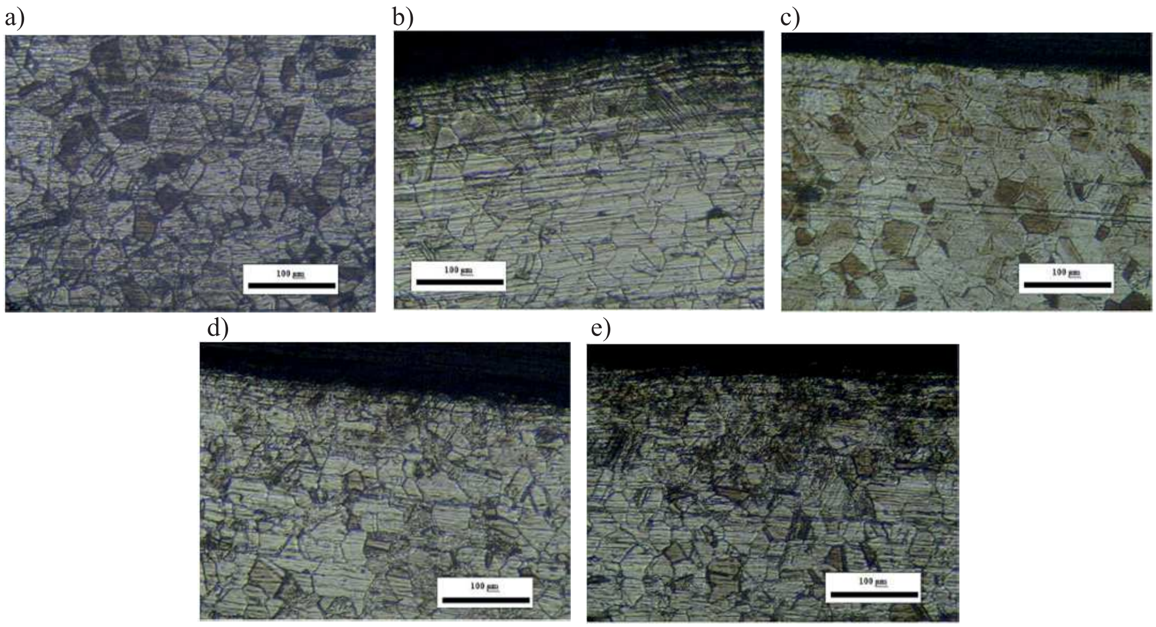

Fig. 3. The microstructure of the shot peening material with a shooting distance of 12 cm: a) NT material, b) 2 minutes, c) 4 minutes, d) 15 minutes, e) 30 minutes

At high-stress level, stress corrosion cracking of 316 stainless steel can develop cracks caused by strain incompatibilities between ferrite and austenite, and cracks propagate along the ferrite and austenite interface [17]. Material surface roughness also has a role in pitting corrosion resistance. Higher surface roughness and heterogeneity are very preferred locations for pit initiation, which destroys the passive region of the sample surface [18].

3.2. Surface hardness

The hardness test result is a Hardness Vickers Number (HVN) value obtained from the calculation by entering data of the indentation diagonal length from the result of the measurement. Figure 4 shows that SS 316L has increased surface hardness from NT material. This shows that the shot peening process increases the surface hardness value of SS 316L. Plastic deformation on the sample surface can improve surface hardness. Martensite layer increases when induced martensite formation in the case of surface deformation and will affect mechanical properties [19]. The complex of microstructure in the area at near surface, the structure consists of nanocrystalline regions, strain and deformation bands and all of those will induce martensitic twin lamellae in the austenitic matrix of a surface-treated type of austenitic stainless steel. Variable surface processing will determine the quantity and depth of martensite, and extended throughout to the area that the plastically strained [20]. The plastic deformation then forms a dislocation density where more plastic deformation occurs, the more dislocation density will develop, thus forming the interaction between dislocations with each other. This interaction will make the dislocation density higher and will inhibit each other causing strain hardening effect.

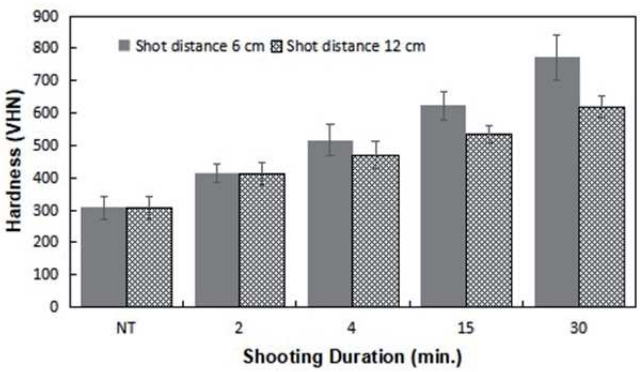

Fig. 4. Hardness value of shot peening SS 316L

The duration of shot peening also affects the surface hardness value of the shot peening material. The longer the duration of the shot peening treatment, the surface hardness will be higher. Increased hardness continues to increase, as the duration of the treatment of shot peening is given. The increased hardness of the material due to the longer duration of shot peening given, there will be a large plastic deformation which will then form a larger density dislocation.

In addition to the duration of shot peening, the shooting distance also affects the hardness value of the shot peening material. At a distance of 6 cm, the hardness value is greater than the material of the shot peening process at a distance of 12 cm. This occurs because of the impact of the shooting intensity provided by each steel ball. The closer the shot, the intensity of the collision of the steel balls will be more and more, that will cause a high plastic deformation. This high plastic deformation will increase the hardness value of the material.

The closer distance and the duration of the shot peening process can increase the hardness of the working layer which is more deeper, that means the speed of impact between the steel-ball and the material surface is higher than greater distance and short duration. The distance and duration will affect the increase in kinetic energy. Increased impact velocity causes the level of plastic deformation and penetration into the sample to increase significantly. The peening process will induce a larger compression zone with a higher subsurface compressive stress.

3.3. Corrosion

In this research, to find the value of corrosion rate is used cyclical polarization method. This method is used to determine the rate of corrosion and the tendency of a material to undergo pitting corrosion. The rate of corrosion of the material is affected by the value of the corrosion current (I_{corr}). Based on Eq. 5, the calculation of the corrosion rate must first calculate the value of the equivalent weight (EW) and the 316L stainless steel density. The values of equivalent weight (EW) and the 316 L stainless steel weighing are 27.85 and 7.99 gr/ml.

Figure 5 shows that the shot peening material has decreased corrosion rate. This decline occurs in both the shot peening process with a distance of 6 cm and 12 cm. The corrosion resistance is increased due to the shot peening treatment. This increase occurs due to a passive layer formation that protects the surface. The emergence of the nanocrystalline layer due to the collisions of these steel balls are able to withstand dislocations, causing a decrease in the rate of corrosion. At 4 minutes duration at 6 cm distance, there is an increase of corrosion rate value compared to 2 min duration. This occurs because of damage to the Cr_2O_3 layer that protects the surface from corrosion.

Figure 6 shows a graph between E_{corr} and I_{corr} of a shot peening specimen for a 6 cm range, while Figure 7 shows a graph between E_{corr} and I_{corr} of a shot peening specimen for a 12 cm range. The curve is the curve of the potential current intensity distribution of the corrosion test by the cycle polarization method. This curve is used to determine the corrosion current density (I_{corr}) at the intersection of the Tafel line and corrosion potential line (E_{corr}).

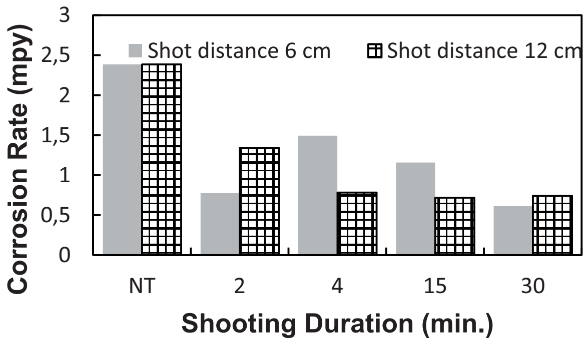

Fig. 5. Corrosion rate of shot peening SS 316L

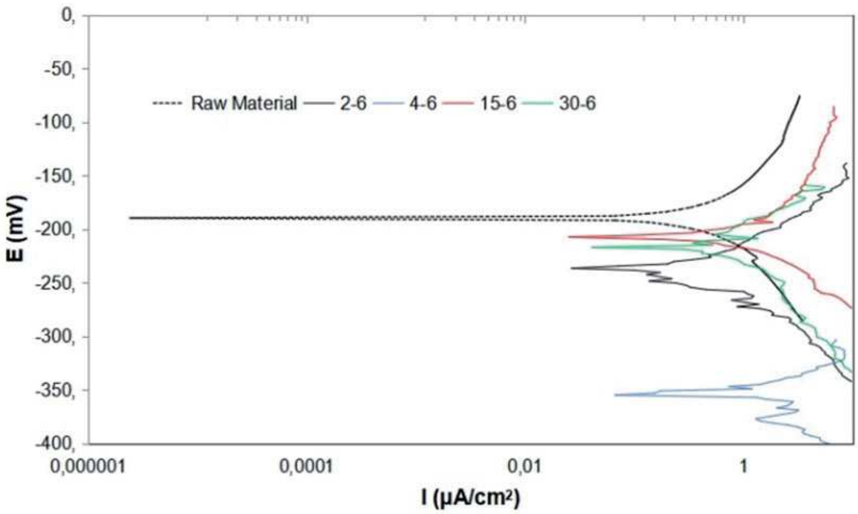

Fig. 6. E_{corr} vs. I_{corr} of the shot peening material with a shooting distance of 6 cm

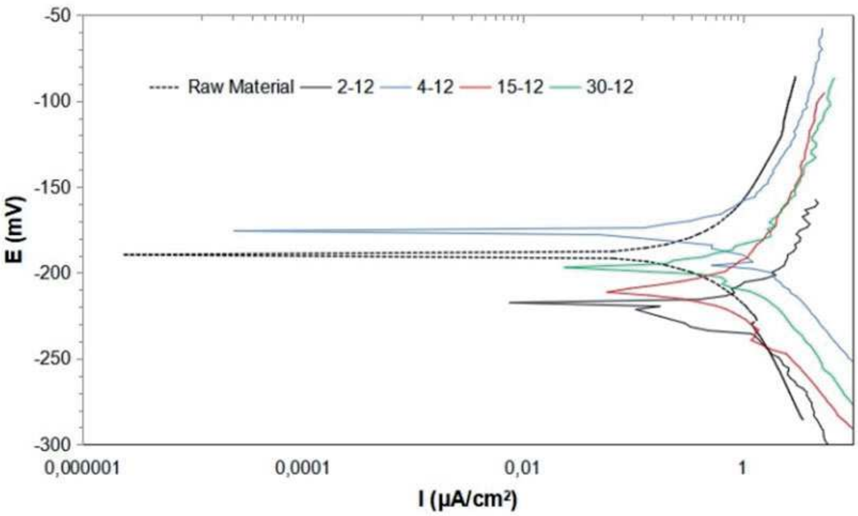

Fig. 7. E_{corr} vs. I_{corr} of the shot peening material with a shooting distance of 12 cm

4. Conclusions

The conclusions about the effect of shot peening on microstructure, hardness, and resistance to corrosion of AISI 316L follows are discussing. The grain structures seem smaller on the near-surface area, which is around 14-28 μm, then it shows increased in the deeper zone, which ranged 31-38 μm. The shot peening treatment of 316L stainless steel material will increase the hardness of the surface, the longer the shooting duration and the closer the shooting distance are used, the hardness will increase. Specimens with shot peening treatment using 6 cm shooting distance and treated for 30 minutes shows the best mechanical properties, which has the highest surface hardness value of 768.15 HVN. Treatment of shot peening on 316L stainless steel material can change the micro-structure on the surface layer. The longer the duration of the shoot, the grain boundary between the small and large grains, farther from the surface, and near the distance, the material will have a grain boundary farther from the surface. In the 316L stainless steel material, the shot peening process can cause increased corrosion resistance, where the corrosion rate decreases with increasing shooting duration and closer distance of shooting.

Closing distance and longer duration of the shot peening process increases the depth of work hardened layer and means a higher impact speed. The distance and duration will affect increased kinetic energy. Increasing impact speed causes the degree of plastic deformation and penetration in the sample to increase significantly. The shot peening process will induce larger compression zones with a higher subsurface compressive stress.

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