coatings

Review

Effects of the Shot Peening Process on Corrosion Resistance of Aluminum Alloy: A Review

Hao Huang [1], Jintao Niu [1,2], Xiangtao Xing [2], Qichao Lin [3], Hongtang Chen [1] and Yang Qiao [1,*]

1 School of Mechanical Engineering, University of Jinan, Jinan 250022, China; huanghao60413@163.com (H.H.); me_niujt@ujn.edu.cn (J.N.); me_chenht@ujn.edu.cn (H.C.)
2 Shandong Kaitai Shot Blasting Machinery Co., Ltd., Binzhou 256217, China; xxtao@126.com
3 Shandong Measurement and Testing Center, Jinan 250014, China; linqichao@sdim.cn
* Correspondence: me_qiaoy@ujn.edu.cn; Tel.: +1-527-510-6865

Abstract: The high humidity of marine atmosphere and the existence of corrosive chloride ions lead to the premature corrosion failure of aluminum alloy components. The development of surface-strengthening technology provides an opportunity to prolong their service life spans. As a mature surface-strengthening technology, the shot peening process is widely used, owing to its advantages over other strengthening technologies, including its easy operation and high production rate. The shot-peened surface integrity depends on shot peening variables that introduces the thermomechanical effect to the deformed surface layer. When the inappropriate shot peening parameters are adopted, the shot-peened surface integrity could be deteriorated, which further weakens the corrosion performance of the surface. Therefore, it is essential to optimize shot peening process variables with the consideration of the material and its application. In this paper, the strengthening mechanism of the shot peening process was firstly elaborated, and then the effects of process parameters on the surface integrity of aluminum alloy were reviewed. The relationship between the surface integrity and corrosion resistance was also revealed. Two directions, including the application of the surface temperature rise during the shot peening process and the shot-peened surface roughening, are proposed.

Keywords: aluminum alloy; shot peening process; strengthening mechanism; surface integrity; corrosion resistance

Citation: Huang, H.; Niu, J.; Xing, X.; Lin, Q.; Chen, H.; Qiao, Y. Effects of the Shot Peening Process on Corrosion Resistance of Aluminum Alloy: A Review. *Coatings* **2022**, *12*, 629. https://doi.org/10.3390/coatings12050629

Academic Editor: Stefanos M. Skolianos

Received: 12 April 2022
Accepted: 30 April 2022
Published: 4 May 2022

1. Introduction

Aluminum alloys are widely used in the aerospace, marine and offshore, and oil and gas fields, as well as in helicopter decks, owing to their high specific strength, low density, excellent processing performance and convenient recycling [1–3].

Aluminum alloy is the basic support material of marine engineering equipment, but the problem of insufficient service ability in harsh corrosion environments has become a bottleneck for its deep application in the ocean [4,5]. Corrosion is the main cause of failure of aluminum alloy components in marine environments, including pitting corrosion, intergranular corrosion, exfoliation corrosion and stress corrosion [6]. From a security point of view, corrosion may cause casualties and shorten aluminum alloy equipment service duration. It was reported that the stress corrosion fracture has happened to an offshore heavy oil pipeline in the atmospheric environment, leading to the leakage of hydraulic fluids [7]. The corrosion may lead to fatigue cracks and brittle fracture of the hull of ocean-going ships and reduce the service life [8]. From an economic point of view, an estimated annual cost resulted from the corrosion of aluminum alloy structural components is over USD 1.8 trillion [9]. Therefore, it is urgent to improve the corrosion resistance of aluminum alloy.

Corrosion of components is not only related to the service environment and material chemical components, but also connected with the components' surfaces' condition, because the surfaces directly contact corrosive ions within the service environment. The surfaces with high corrosion resistance firstly react with these ions at a lower speed, and further protect the base material by restraining ions from entry.

Components with specific geometric and dimensional specifications to meet the corresponding functional requirements are the result of additive manufacturing or subtractive manufacturing [10]. Affected by the effects of heat and force that generated during machining processes, mechanical properties of machined surfaces differ greatly from those of base materials, which further influences their corrosion resistances. Scratches and microcracks on machined surfaces, microstructure, and stress within a layer beneath machined surfaces are all the results of machining processes, and all influence corrosion resistances of machined surfaces. As shown in Figure 1, corrosion develops into interior material from the surface via the defects. With time, under the effect of corrosion, the bulges fall off from the surfaces [11]. Therefore, the machined surface directly affects the corrosion resistance of aluminum alloy.

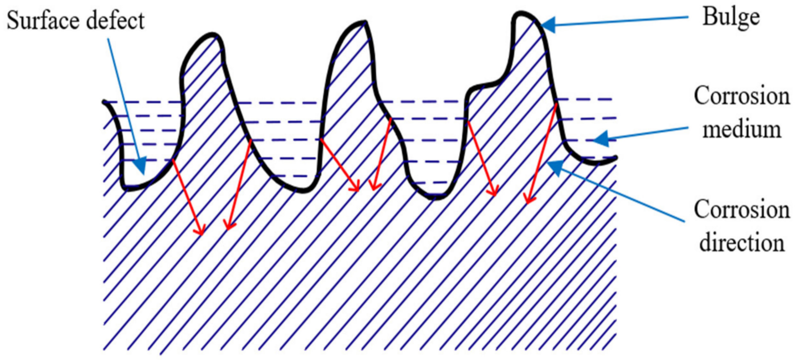


Figure 1. Schematic diagram of surface corrosion development [11].

Surface-strengthening treatments are developed to improve materials' corrosion behaviors [12,13]. Among the treatments, the deformation strengthening is performed by plastic deformation of the material surface introduced by rolling, laser shock, shot peening and other mechanical means. There are two kinds of changes within the deformation layer. One is the changes of microstructure, including grains refinement, dislocation-density increases and texture alteration. The other one is the stress state within the deformation layer. More specifically, there is always a compressive stress field within the layer, which is generally regarded as beneficial to enhance the corrosion resistance [14,15]. Compared with other surface treatments, including rolling and burnishing with similar effects, the shot peening process has been proven to be more effective, because of the size and shape of the to-be-treated workpiece with fewer restrictions, ease of operation and high production rate, despite increasing surface roughness [16,17]. Moreover, the shot peening process can significantly change the surface integrity of the target material, and thus promise to improve the mechanical properties and fatigue strength of critical parts [18]. Lei et al. [19] reported that the shot peening process induced cementite dissolution and the formation of nanoparticles, contributing positive effects on the corrosion behavior of the SA106B low-carbon steel. The interesting work of Kumar et al. [20] proposed that Ti-13Nb-13Zr alloy after the ultrasonic shot peening process showed a lower corrosion rate. Studies have shown that the shot peening treatment significantly affects the corrosion resistance of the material.

To date, there have been many publications on the effect of shot peening treatment on the corrosion resistance of aluminum alloys, but a comprehensive review on this topic is still lacking. In this paper, the strengthening mechanism of the shot peening process was firstly elaborated, and then the effects of process parameters upon surface integrity of aluminum alloys were discussed. Finally, the influence mechanism of surface integrity on corrosion resistance of aluminum alloy was reviewed.

2. Strengthening Mechanism of Shot Peening Process

Shot peening is a mature, surface-treatment technology, with the aim to enhance the resistance to cyclic load and stress corrosion of components [21]. Its mechanism mainly includes the mechanism of microstructure strengthening and stress strengthening, as respectively shown in Figures 2a,b [22,23]. With a large number of high-speed shots (such as cast steel shots, cast iron shots, glass shots, ceramic shots) repeatedly impacting the surface of the metal workpiece, the dislocation density and distorted grains within the surface layer increase greatly, constituting a microstructure-strengthening mechanism. Additionally, a residual compressive stress field with good thermal stability is generated within the surface layer, forming a stress-strengthening mechanism [24]. Besides the two mechanisms mentioned above, an effect is also introduced by the shot peening process, namely surface roughening effect, which is generally considered as its side effect.

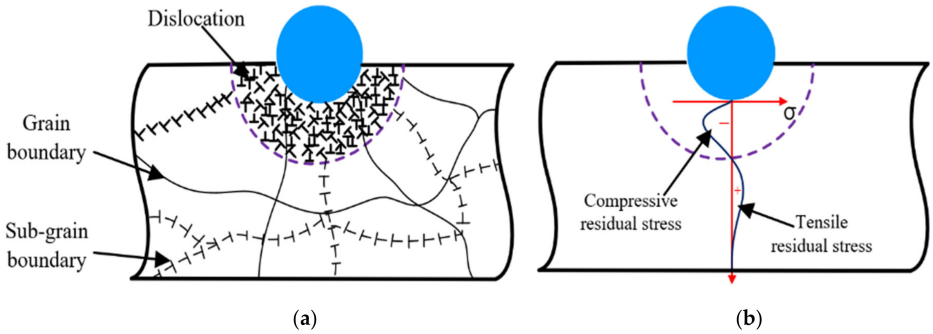


Figure 2. Schematic diagram of traditional shot peening process strengthening mechanism: (**a**) microstructure strengthening; (**b**) stress strengthening [23].

The degrees of microstructure strengthening, stress strengthening and surface roughening are determined by the combination of shot peening parameters, including shot type and size, Almen intensity and surface coverage. Almen intensity is the industrial measure of kinetic energy generated by shot impact on the specimen, while surface coverage is considered to be the ratio of impact surface pits to total area [25,26]. An inappropriate combination of process variables could cause an over- or under-treated surface. The former condition weakens the strengthening effect, while the latter one even leads to a worse resistance to corrosion of treated surfaces than those of not treated ones [27,28]. For example, when cracks are present on peened surfaces, their corrosion properties necessarily worsen.

Surface service behaviors, such as corrosion resistance and fatigue property, depend on surface integrity, including microhardness [29], surface residual stress [30], surface roughness [10] and microstructure [31], as depicted in Figure 3 [32]. Under the same conditions, the higher the surface-integrity level, the better the corrosion resistance of the material [33,34]. To meet production needs, a series of new shot peening technologies have been developed, such as laser shock shot peening [35,36], ultrasonic shot peening [37] and high-pressure waterjet shot peening [38], as shown in Table 1.

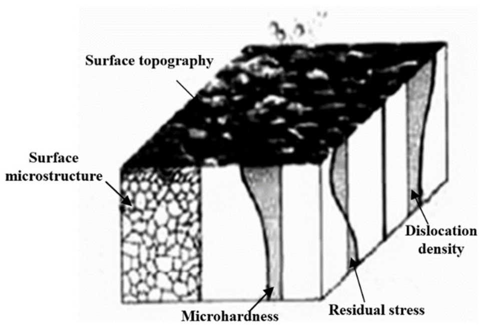


Figure 3. Surface integrity and their corresponding distribution after shot peening [32].

Table 1. Different shot peening techniques and their characteristics.

Variety	Impact Medium	Parameter	Characteristics
Shot peening	Shot	Shot material and size Almen intensity Surface coverage Impact angle	The size and shape of the to-be-treated work piece with fewer restrictions, ease of operation as well as high production rate.
Laser shock peening	Laser beam	Power density Pulse duration Absorbent coating	Better surface finish, higher depths of residual stress and uniform distribution of intensity.
Ultrasonic shot peening	Spherical tip/Shot	Frequency Amplitude Static load Ball diameter	The equipment has the advantages of small volume, low energy consumption and environmental protection.
High-pressure waterjet shot peening	Mixed water beam mixed with shot	Supply pressure Jet exposure time Nozzle traverse rate	Simpler control over the process, full coverage of the treated area, flexibility in treating complex areas and ecofriendly environment.

3. Effect of the Shot Peening Process on Surface Integrity of Aluminum Alloy

Shot peening process results in the enlargement of surface roughness, the generation of residual compressive stress and work hardening within the surface layer, which affects the corrosion resistance of aluminum alloy [39]. The influence of the shot peening process on the surface integrity of aluminum alloy is shown in Table 2. For a given material, the various surfaces in terms of surface integrity possess different corrosion resistances. By optimizing the process parameters, high surface integrity can be obtained. The traditional shot peening parameters are depicted in Figure 4.

Table 2. Surface integrity variation of aluminum alloy before and after the shot peening process.

Materials	Parameters	Before Treatment	After Treatment
2124-T851 [40]	Surface roughness Ra (μm)	0.75	7.20
AlSi10Mg [18]	Residual stress (MPa)	7.7 ± 5	-152.5 ± 7
7475-T7351 [41]	Maximum residual stress depth (μm/beneath the surface)	0	45
AA2024 [29]	Surface microhardness (HV)	65	140

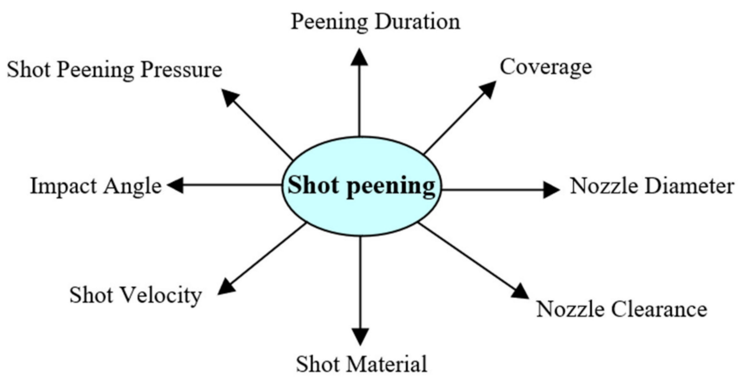


Figure 4. Traditional shot peening parameters [42].

3.1. Surface Roughness

Caused by multiple overlapping dimples in shot peening, surface roughness can be intervened with shot peening parameters. Tuning the set of peening parameters can reduce and even totally mask the undesirable effects of surface roughness. This has been recognized as a challenge, especially for aluminum alloys.

Win et al. [43] reported that the surface roughness of AA7075-T6 aluminum alloy is closely related to the shot peening pressure. They found that the surface roughness (i.e., S_a, S_q, S_p and S_v) of the sample increased significantly with the increase in shot peening pressure, as shown in Figure 5. Pandey et al. [44] conducted shot peening experiments on 7075 aluminum alloy with an ultrasonic shot peening operation. They found that the surface roughness of the test workpiece increased with the increase in shot peening duration. Interestingly, at the initial stage of shot peening, the surface roughness increased more rapidly. With time, the surface roughness increased slowly, and its magnitude was almost constant.

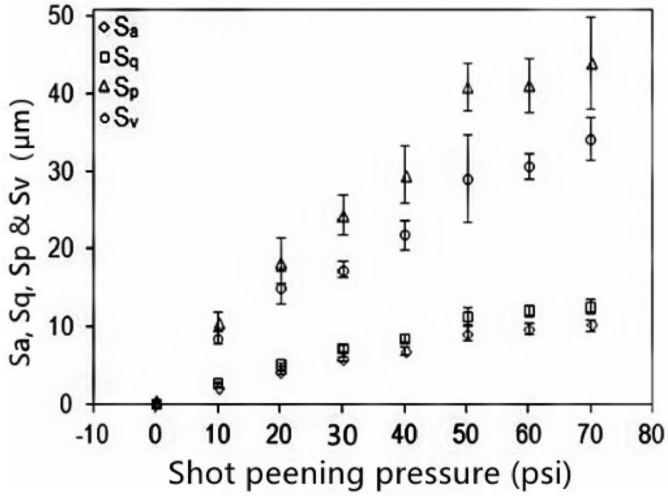


Figure 5. S_a, S_q, S_p and S_v values of shot-peened surfaces of AA7075-T6 with various shot peening pressures [43].

Advanced analytical and numerical tools can optimize process parameters with a sustainable cost and maximize shot peening efficiency [45]. A glass-shot impact model was established by Zhang et al. [46] with ABAQUS for a theoretical prediction. They found that with the increase in shot peening coverage, the surface roughness of 7075 aluminum alloy increases first and then decreases. Then some shot peening experiments were performed, which verified the above conclusion.

Recently, many experiments usually describe the influence of a single factor on surface characteristics, but the influence of a multifactor combination is also very obvious. Sheng et al. [47] took 7075-T651 aluminum alloy as the research object to study the shot-peened surface roughness with different process-parameter combinations. Through finite-element-simulation calculation and experimental test, they found that larger shot size and lower shot velocity can effectively reduce the surface roughness with a constant shot peening pressure. Liu et al. [48] explored the change of 7075-T651 aluminum alloy surface roughness using 3D simulation modeling and shotting experiments. The results showed that with an increase in the shot peening pressure and shot size, the plastic deformation of alloy surface was severe, and the roughness tends to increase. However, with the increase in shot peening distance and coverage, the depth of craters decreases, and the surface roughness will decrease gradually. Therefore, combinations of reasonable shot peening parameters should be selected to obtain the desired surface roughness during shot peening of aluminum alloy.

3.2. Residual Stress

Residual stress is an indispensable factor in improving the fatigue resistance and corrosion resistance of materials. Its magnitude and distribution depend on shot peening parameters.

On the one hand, the shot peening process parameters affect the distribution of residual stress field on the surface of aluminum alloy. The effect of different shot peening pressures on the corrosion behavior of 7075 aluminum alloy was investigated [49]. The research results showed that the magnitude of residual stress on the shot-peened surface increased with the increase in shot peening pressure. On the other hand, it greatly affects the maximum residual stress depth. Based on the numerical simulation and experimental study of shot peening Al-Li alloy, Wang et al. [50] found that with the increase in shot size, the depth of the residual stress layer increased significantly, and the magnitude of residual stress also increased, indicating that shot size significantly affected the residual stress, as shown in Figure 6. These observations are mainly attributed to the increasing kinetic energy produced by the shot when increasing the shot size, which promotes the plastic deformation development within the surface layer. Miao et al. [51] took 2024 aluminum alloy as the research object to study the influence of shot peening duration on residual stress distribution. With the increase in shot peening duration, the number of shots impacting the surface increases, and the maximum compressive stress near the surface and the maximum tensile stress depth of the material increases continuously.

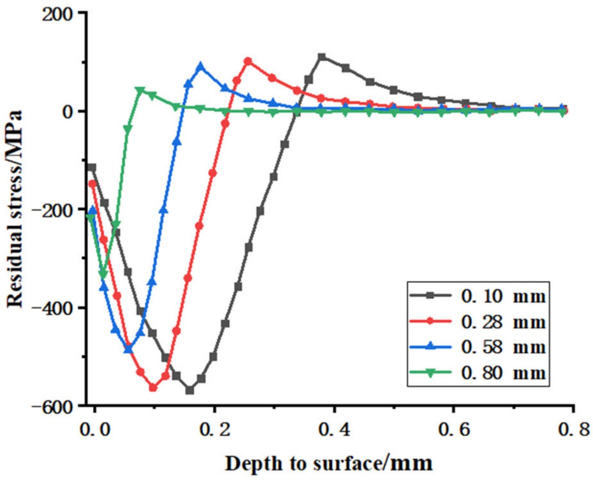


Figure 6. Influence of shot size on residual stress distribution [50].

Studies have shown that the maximum residual compressive stress of the workpiece after shot peening is 50% to 60% of the ultimate tensile stress of the material, which indicates that the residual compressive stress cannot increase infinitely after shot peening [52]. Zhao et al. [53] investigated the effects of shot peening intensity, coverage and surface integrity on the fatigue properties of 2024HDT-T351 aluminum alloy after the shot peening process. The research results showed that the surface residual compressive stress was closely related to the shot peening parameters, and the surface residual compressive stress did not increase monotonically with the increase in shot peening intensity, but increases first and then decreases.

3.3. Surface Microhardness

Different shot peening parameters affect the surface microhardness of aluminum alloy. The microhardness of the material after shot peening is applied to characterize the cold work hardening properties of the material [54].

Through the research on the effect of the shot peening process on the surface integrity of a 7075 aluminum alloy sample, Li et al. [55] found that mechanical shot peening could improve the surface microhardness, and its value increased with the increase in shot peening pressure and shot size. Zhu et al. [56] investigated the effect of ultrasonic shot peening on the surface microhardness of 7075 aluminum alloy. It was found that with the decrease in shot peening distance, the surface microhardness of 7075 aluminum alloy gradually increased and the average hardening rate increased.

Compared with coverage rate, shot peening pressure is the key parameter affecting microhardness. Avcu et al. [57] reported this rule after shot peening AA1050 aluminum alloy. After shot peening, the microhardness of the samples increased under different shot peening pressures and coverage rates, and the microhardness within the surface layer decreased gradually beneath the surface, as shown in Figures 7a,b. The surface microhardness increased by 22% at higher pressure, whereas different coverage rates had an insignificant effect on the microhardness.

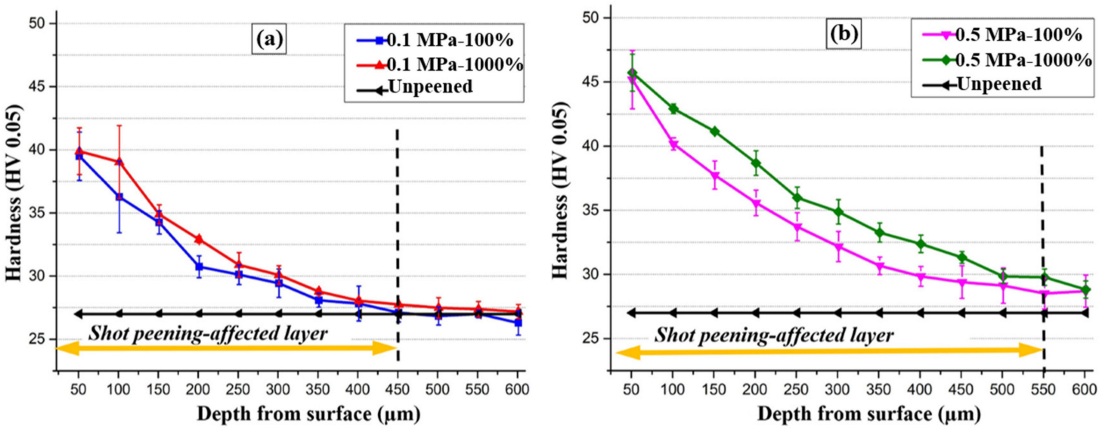


Figure 7. Change in microhardness along depth direction under different coverage rates and peening pressures: (**a**) 0.1 MPa; (**b**) 0.5 MPa [57].

In another study, where the 5052 Al alloy sheet was shot-peened, Li et al. [58] found that with the extension of shot peening duration, the microhardness along the whole thickness of the sample was improved, meaning the deformation penetrated the whole thickness. However, the microhardness of the samples treated for 10 min within 0–100 μm beneath the shot-peened surface was lower than that of the samples treated for 5 min, and also lower than that of the samples treated for 2.5 min in some ranges, as shown in Figure 8. These observations are mainly attributed to the fact that with the extension of shot peening duration, the surface temperature of the sample increases, which induces the dynamic recovery within the deformed layer and resultantly reduces the microhardness. This revealed that the shot peening process not only introduces the cold-hardening effect to the material, but also induces the softening effect due to the temperature rise during a shot peening operation [59]. Making use of the temperature rise is a potential direction, which is being investigated in our parallel study.

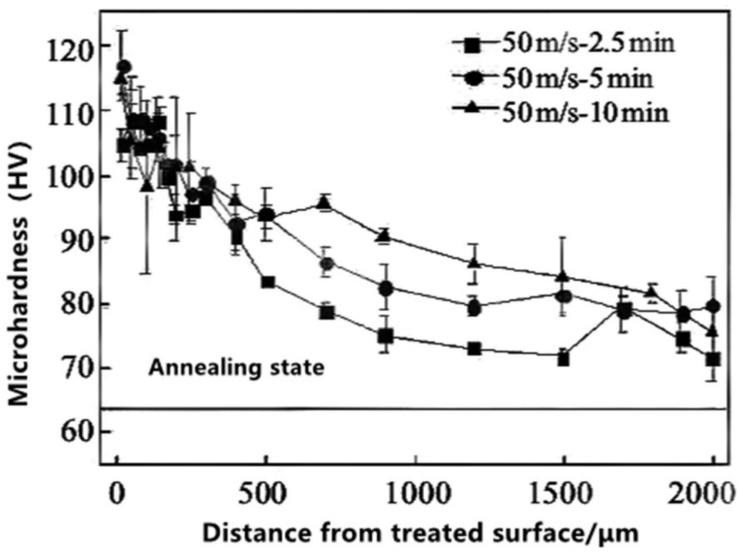


Figure 8. Microhardness distribution of 5052 aluminum alloy along depth direction after shot peening process with different durations [58].

4. Effect of a Deformed Surface Layer on Corrosion Resistance of Aluminum Alloy

Shot peening technology plays an extremely important role in improving the corrosion resistance of machined surfaces.

Yang et al. [60] conducted shot peening on 319s aluminum alloy, and measured their corrosion resistance with a salt-spray test in sodium chloride solution. The results showed that the average corrosion weight loss of the surfaces after the shot peening process significantly reduced, and the initiation and expansion of pitting defects were inhibited. Ye et al. [61] investigated the effects of shot peening and stress factors on the corrosion behavior of 2E12-T3 aluminum alloy. The results showed that after the shot peening process, the exfoliation corrosion sensitivity significantly reduced. After 96 h of corrosion, the surface of the sample without shot peening was reddish brown, and a large number of oval bubbles appeared. However, after shot peening, there was no obvious bubbling on the shot-peened surfaces, and exfoliation corrosion was the main corrosion form. The corroded surface morphology of these two kinds of samples (i.e., with and without the shot peening process) is respectively shown in Figures 9a,b. Table 3 lists the effects of the shot peening process on the corrosion resistance of aluminum alloy by comparing the corrosion parameters. The enhanced corrosion resistance was attributed to the grain-refined surface layer, texture alteration, and compressive residual stresses.

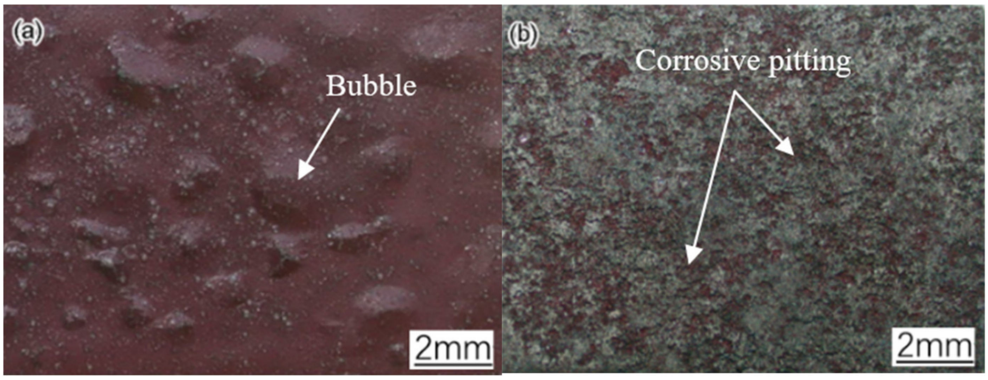


Figure 9. Corroded surface morphology of 319s aluminum alloy samples: (**a**) without shot peening; (**b**) with shot peening [61].

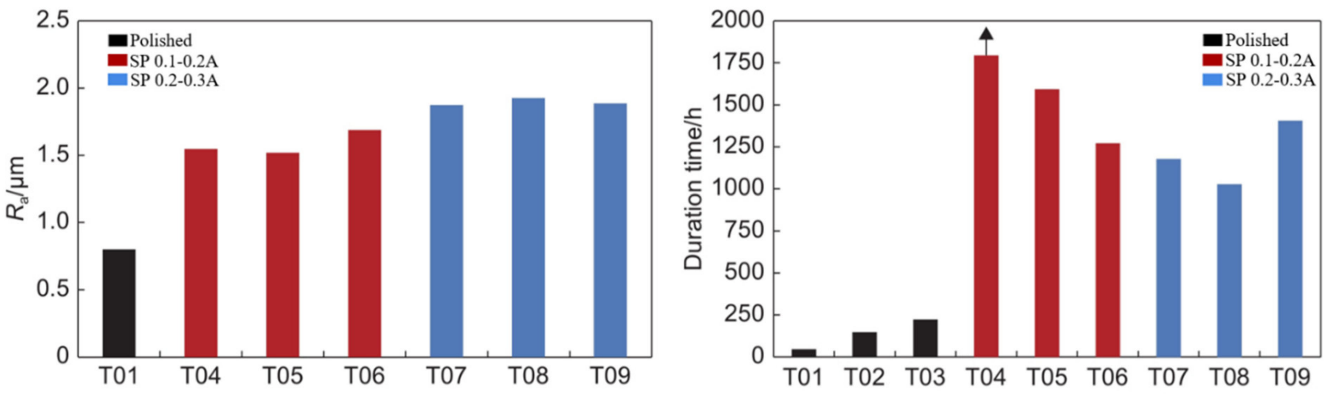
Table 3. Effect of shot peening process on corrosion resistance of aluminum alloy.

Materials	Corrosion Parameters	Before Treatment	After Treatment	Conclusion
AA7075 [62]	corrosion rate (μm/year)	44.19	20.06	Shot peening process can significantly reduce the corrosion rate of samples.
AA2024 [63]	corrosion depth (μm)	192 ± 54	107 ± 30	Shot peening process can significantly reduce the depth of corrosion.
AA7150 [64]	corrosion potential (V)	−0.775	−0.739	Pitting potential shifts to the more anodic direction after shot peening process, indicating an improved initiation resistance of localized corrosion.
AISI 304SS [65]	corrosion current density (μA/cm^2)	0.9	0.3	After shot peening process, the corrosion current density decreased compared to that of the original sample.

4.1. Surface Roughness

Although alternative applications that can benefit from shot-peening-induced delamination surface roughness are being explored, surface roughness may adversely affect most common industrial applications, such as corrosion resistance.

Several studies have shown that the corrosion resistance of a material is inversely proportional to its surface roughness [66]. He et al. [67] investigated the effects of different shot peening intensities on stress corrosion resistance of 7B04-T6 aluminum alloy. The results show that the duration of stress corrosion is related to surface roughness. It can be seen from Figures 10a,b that the surface roughness of samples T07–T09 after shot peening is larger, and consequently the stress corrosion duration is shorter when compared with samples T04–T06. These observations are mainly attributed to the increased shot-peened surface roughness leading to an increase in the actual total contact area of the material surface with the corrosion solution, which further increases the probability of stress corrosion cracking of the material.



(**a**) (**b**)

Figure 10. Surface roughness and duration of stress corrosion under different shot peening intensities. (**a**) Surface roughness; (**b**) stress corrosion cracking duration [67].

Mhaede et al. [68] discussed the effect of the surface state of AA7075-T73 aluminum alloy after shot peening on corrosion fatigue performance. The electrochemical tests performed in an NaCl solution showed that for shot-peened samples, their corrosion resistances notably reduced. The higher reactivity of the shot-peened surfaces was attributed to the higher surface roughness providing additional active anodic sites on the surface.

4.2. Residual Stress

After shot peening, the sample surface would be in the state of residual compressive stress. It is one of the surface integrity parameters that cannot be ignored for high-performance aluminum alloy [69].

The introduction of residual compressive stress could offset part of applied stress on aluminum alloy surface and external thrust generated by grain-boundary corrosion products, which could inhibit the occurrence of metal-surface corrosion effectively. Trdan et al. [70] compared the corrosion behavior of AA6082-T651 aluminum alloy in a 0.6 M sodium chloride solution before and after laser shot peening with electrochemical polarization tests. As can be seen from Figures 11a,b, after the corrosion test, large pits are distributed on the entire surface of the sample without laser shot peening, while the size and number of pits on the peened sample surface were greatly reduced. The difference was mainly attributed to the high residual stress introduced by laser shot peening. Lv et al. [71] investigated the effect of shot peening on the corrosion behavior of 7050 aluminum alloy in a peeling solution. They observed that the corrosion depth of the sample after shot peening was significantly lower than that of the untreated sample, which is the result of the existence of a residual compressive stress field.

Additionally, the residual stress induced by shot peening was reported to affect the passivation film on the surface of 7075 aluminum alloy [72]. The surface residual compressive stress induced by laser shot peening improved the transverse compressive force of AlOOH passivation film, which enhanced the corrosion potential and pitting potential of aluminum alloy plasma arc welding joints.

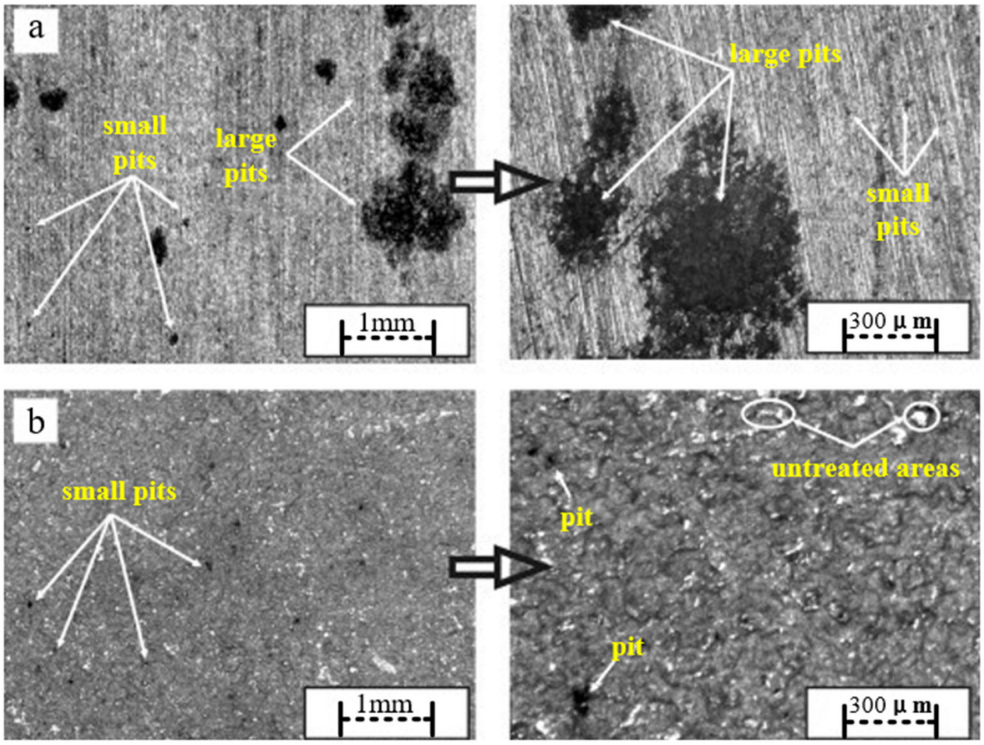


Figure 11. Changes of pits on the corroded surfaces of AA6082-T651 aluminum alloy. (**a**) Without laser shot peening; (**b**) with laser shot peening [70].

Abdulstaar et al. [73] investigated the effect of shot peening on the corrosion resistance of 5083 aluminum alloy. The results show that after shot peening, the limited residual stress and stress depth reduced the surface corrosion resistance and accelerated alloy surface corrosion. Therefore, an appropriate residual stress field can effectively improve the corrosion resistance of aluminum alloy, while too high or too low residual stress leads to accelerated corrosion.

4.3. Microstructure

The variation of the stress field and microhardness on and beneath the shot-peened surface indicates the existence of a deformed surface layer, which is the result of microstructure change, including dislocation density enlargement and grain refinement.

It is generally believed that the microstructure refinement mechanism of the shot-peened surface layer is that the contact stress exceeds the yield strength of the metal material under cyclic impact, resulting in a strong plastic deformation of the material in different directions. Plastic deformation is concentrated in the metal surface layer, resulting in the continuous increase in surface dislocation density. Moreover, with the continuous proceeding of the shot peening process, defects such as dislocation, twin stacking fault and shear band appear within the surface plastic deformation layer. Under the interaction of these defects, they are continuously annihilated and reorganized, and finally evolve into micro-nano scale cellular structures, subgrains and grains [74–76]. The formation process of microstructure refinement is shown in Figure 12.

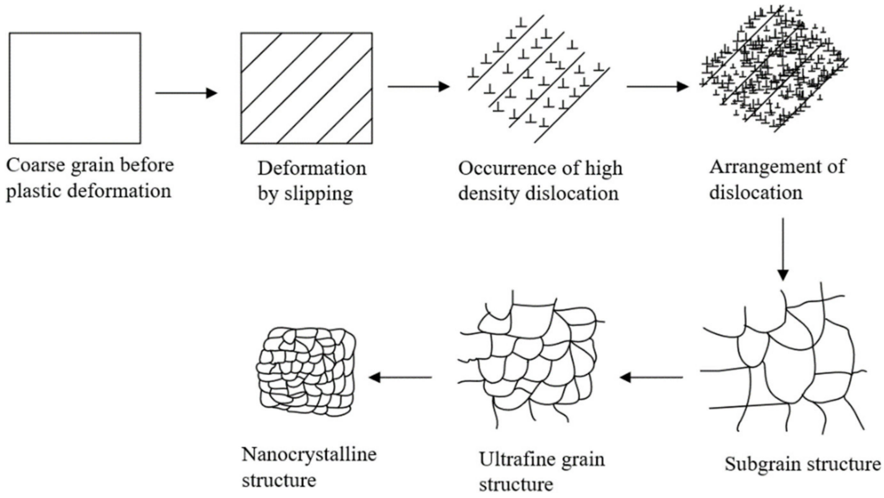


Figure 12. Formation process of microstructure refinement [77].

The microstructure of a material affects its service performance. The volume fraction of grain boundary on the surface of the material increases after the shot peening process, which is significantly effective in enhancing corrosion resistance. Amini et al. [78] investigated the effect of an ultrasonic shot peening process on the corrosion behavior of 7075 aluminum alloy, and found that the corrosion current density of the peened sample was much lower than that of the original one, indicating that the corrosion resistance of the former specimen was significantly improved. This was because the grain refinement caused by the shot peening process increased the grain boundary volume fraction on the surface, as shown in the Figure 13. At the same time, the microstructure tends to be uniform and the local corrosion is alleviated. Grain refinement can effectively prevent the occurrence of stress corrosion fractures. Laser shot peening was applied to 2195 aluminum alloy to investigate its effect on stress-corrosion performance [79]. Severe process parameters lead to grain refinement and greatly increase the proportion of grain boundaries. A large number of grain boundaries would increase the resistance of crack propagation, making it difficult for the corrosion cracks to grow and infiltrate.

The formation of passive film is also an important factor in improving the corrosion resistance of aluminum alloy. Corrosion behavior of Ni-Al bronze alloy after the shot peening process was investigated through experiments with different shot peening pressures [80]. The results show that the corrosion current density of the material after the shot peening process decreased, which is shown in Figure 14a. These observations are mainly attributed to the refined and homogenized microstructure, which is conducive to the rapid formation of protective passivation film. However, the opposite conclusion was obtained through the analysis of electrochemical impedance spectroscopy. The diameter of the impedance arc of the shot-peened sample was smaller than that of the as-cast sample, as shown in Figure 14b. In order to avoid the contradictory conclusions regarding the corrosion resistances of given materials drawn by traditional corrosion parameters, Niu et al. [81,82] proposed for the first time to compare the corrosion resistance with some novel indicators, such as the polarization current density, corrosion equivalent resistance, charges passing through materials and material mass loss. These indicators are obtained using potentiostatic polarization measurements.

Although grain refinement has a significant influence on corrosion resistance, the increase in dislocation and grain boundary/subgrain boundary can also provide more channels for the inward diffusion of a corrosion medium [83]. Therefore, whether the corrosion behavior of the shot-peened surface improves or not, and if so, how much improvement can be made after a shot peening operation. are two questions that need much more attention. Based on these questions, the optimization of the shot peening process parameters is particularly important. Understanding the relationship among the process parameters, the shot-peened surface integrity and its corrosion resistance is helpful to the optimization process. The simulation operation of the shot peening process can be an effective tool [84].

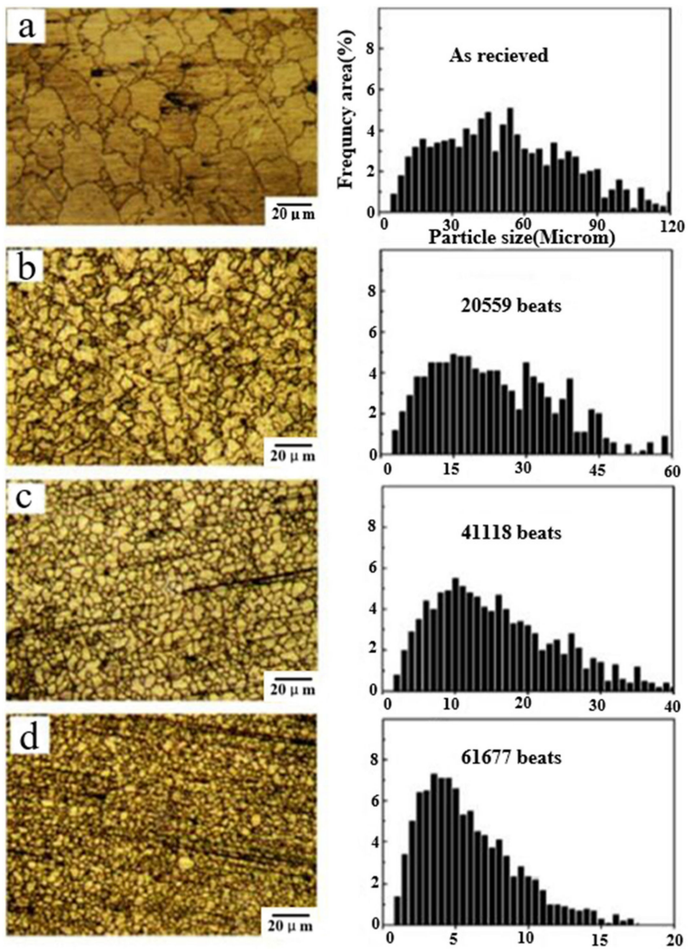
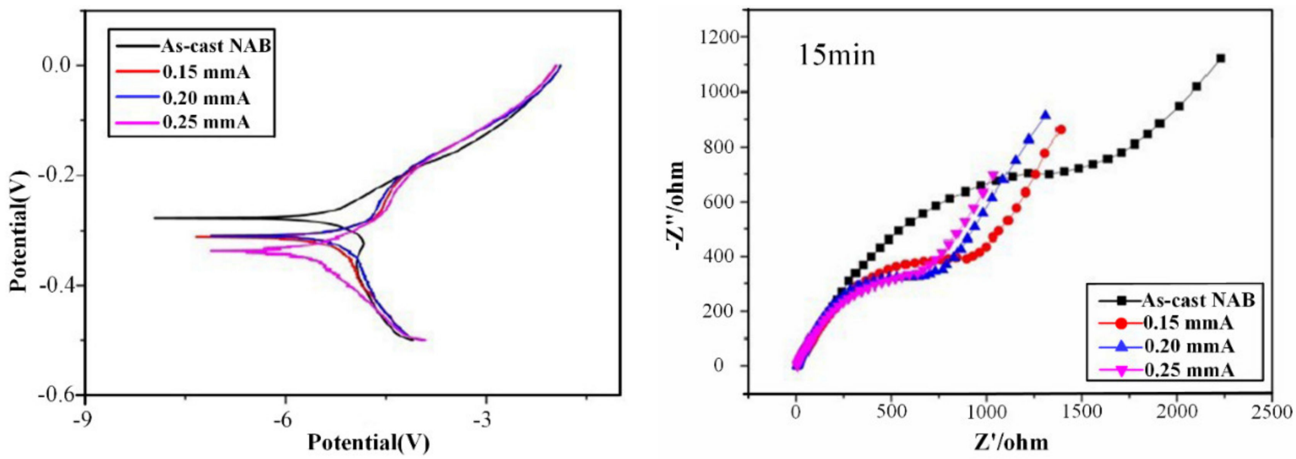


Figure 13. Microstructure and grain distribution under different ultrasonic shot peening times. (**a**) Original material; (**b**) after 20,559 beats ultrasonic peening; (**c**) after 41,118 beats ultrasonic peening; (**d**) after 61,677 beats ultrasonic peening [78].



(**a**) (**b**)

Figure 14. Polarization curve and Nyquist curve of as-cast NAB and samples with different shot peening intensity immersed in 3.5 % NaCl solution for 15 min. (**a**) Polarization curve; (**b**) Nyquist curve [80].

5. Summary and Outlook

The shot-peened surface integrity of aluminum alloy can be effectively changed with the shot peening process under the thermomechanical effect. An inappropriate process variable may even deteriorate the service behavior of aluminum alloy. Therefore, the shot peening parameters should be optimized according to the target material and use conditions. The simulation of the shot peening process should be widely used in the future because it is time-saving and economical.

The formation of the passive film on aluminum alloy surface is related to the microstructure and residual stress field, and they are affected by the surface temperature rise during the shot peening process. Therefore, tuning the shot peening parameters (such as increasing shot peening time and shot peening intensity) and establishing a temperature field on the surface to promote the formation of the passive film and ultimately improve the surface corrosion behavior is a potential direction.

Microstructure strengthening and stress strengthening introduced by the shot peening process improve mechanical properties of aluminum alloy surface. However, it also introduces a side effect, namely, the surface-roughening effect. To further improve the corrosion resistance of aluminum alloy in marine environments, future efforts should be paid to improve the bonding strength between subsequent coating and aluminum alloy shot-peened surfaces by taking advantage of the surface-roughening effect.

Author Contributions: Conceptualization, H.H. and J.N.; Methodology, Y.Q. and H.C.; Investigation, H.H., J.N.; Y.Q.; H.C.; X.X. and Q.L.; Writing—Original, Draft Preparation, H.H.; Writing—Review and Editing, H.H., J.N.; Y.Q., H.C.; X.X. and Q.L.; Supervision, X.X.; Project Administration, Y.Q. and Q.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shandong Higher Education Youth Innovation and Technology Support Program (2019KJB021), the Natural Science Foundation of Shandong Province (ZR2019QEE032) and the Independent Innovation Team Foundation of Jinan (2019GXRC012).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Santos, M.C.; Machado, A.R.; Sales, W.F.; Barrozo, M.A.S.; Ezugwu, E.O. Machining of aluminum alloys: A review. *Int. J. Adv. Manuf. Tech.* **2016**, *86*, 3067–3080. [CrossRef]
2. Hirsch, J. Aluminium in innovative light-weight car design. *Mater. Trans.* **2011**, *52*, 818–824. [CrossRef]
3. Robinson, J.S.; Pirling, T.; Truman, C.E.; Panzner, T. Residual stress relief in the aluminium alloy 7075. *Mater. Sci. Technol.* **2017**, *33*, 1765–1775. [CrossRef]
4. López-Ortega, A.; Areitioaurtena, O.; Alves, S.A.; Goitandia, A.M.; Elexpe, I.; Arana, J.L.; Bayón, R. Development of a superhydrophobic and bactericide organic topcoat to be applied on thermally sprayed aluminum coatings in offshore submerged components. *Prog. Org. Coat.* **2019**, *137*, 105376. [CrossRef]
5. Mariana, P.M.V.; Abrahami, S.T.; Hack, T.; Malte, B.; Herman, T. A review on anodizing of aerospace aluminum alloys for corrosion protection. *Coatings* **2020**, *10*, 1106.
6. Zhang, B.; Fang, Z.; Li, X.Y.; Dong, C.C. Current status and prospect of corrosion protection technology for aluminum alloy ships. *China Mater. Prog.* **2014**, *33*, 414–417. (In Chinese)
7. Qiu, C.J.; Zhou, X.J.; Shi, Z.B.; Liu, H.J. Fracture analysis of steam huff and puff pipeline in a well in Bohai Sea. *Coat. Prot.* **2019**, *40*, 16–26. (In Chinese)
8. Soares, C.G.; Garbatov, Y.; Zayed, A.; Wang, G. Influence of environmental factors on corrosion of ship structures in marine atmosphere. *Corros. Sci.* **2009**, *51*, 2014–2026. [CrossRef]
9. Li, B.; Dong, L.H.; Wang, H.D.; Zhou, Y.X.; Gao, C. Research Progress on Corrosion Fatigue of Aerospace Aluminum Alloy. *Surf. Technol.* **2021**, *50*, 106–118. (In Chinese)
10. Niu, J.T.; Liu, Z.Q.; Wang, G.J.; Huang, W.M.; Xu, Y. Anticorrosion property enhancement of Al–Li alloy 2A97 by lowering machined surface roughness. *Mater. Corros.* **2020**, *71*, 1980–1988. [CrossRef]

11. Chen, G.J.; Hou, S.; Han, S.X. Research Progress on the Influence of Machining Surface Quality on corrosion Resistance. *Surf. Technol.* **2019**, *48*, 25–33. (In Chinese)
12. Bhat, K.U.; Panemangalore, D.B.; Kuruveri, S.B.; John, M.; Menezes, P.L. Surface Modification of 6xxx Series Aluminum Alloys. *Coatings* **2022**, *12*, 180. [CrossRef]
13. Wang, H.; Ning, C.; Huang, Y.; Cao, Z.; Chen, X.; Zhang, W. Improvement of abrasion resistance in artificial seawater and corrosion resistance in NaCl solution of 7075 aluminum alloy processed by laser shock peening. *Opt. Lasers Eng.* **2017**, *90*, 179–185. [CrossRef]
14. Cheng, J.C.; Zhou, X.Y.; Zhou, T.; Zhang, Y.W.; Yang, T. Research Status and Prospect of Surface Strengthening Technology for Automotive Parts. *Surf. Technol.* **2015**, *44*, 68–75. (In Chinese)
15. Deng, H.H.; Xia, Q.X.; Cheng, X.Q.; Ren, Y.P. Effect of shot peening on fatigue properties of pre-corroded aluminum alloy. *Surf. Technol.* **2016**, *45*, 118–123. (In Chinese)
16. Meyer, D.; Hettig, M.; Mensching, N. Pulsed Mechanical Surface Treatment—An Approach to Combine the Advantages of Shot Peening, Deep Rolling, and Machine Hammer Peening. *J. Manuf. Mater. Process.* **2021**, *5*, 98. [CrossRef]
17. Jerez-Mesa, R.; Llumà, J.; Travieso-Rodríguez, J.A. Vibration-Assisted Ball Burnishing. *Encyclopedia* **2021**, *1*, 460–471. [CrossRef]
18. Maamoun, A.H.; Elbestawi, M.A.; Veldhuis, S.C. Influence of Shot Peening on AlSi10Mg Parts Fabricated by Additive Manufacturing. *J. Manuf. Mater. Process.* **2018**, *2*, 40. [CrossRef]
19. Lei, C.; Chen, X.; Li, Y.; Chen, Y.; Yang, B. Enhanced Corrosion Resistance of SA106B Low-Carbon Steel Fabricated by Rotationally Accelerated Shot Peening. *Metals* **2019**, *9*, 872. [CrossRef]
20. Kumar, P.; Mahobia, G.S.; Mandal, S.; Singh, V.; Chattopadhyay, K. Enhanced corrosion resistance of the surface modified Ti-13Nb-13Zr alloy by ultrasonic shot peening. *Corros. Sci.* **2021**, *189*, 109597. [CrossRef]
21. Azhari, A.; Sulaiman, S.; Rao, A.K.P. A review on the application of peening processes for surface treatment. *IOP. Conf. Ser. Mater. Sci. Eng.* **2016**, *114*, 012002. [CrossRef]
22. Zhang, S.B.; Bu, Z.Y. Finite Element Simulation of residual stress field of 2024 Aluminum Alloy after random multi-shot peening. *Mater. Mech. Eng.* **2016**, *40*, 87–90.
23. Wang, R.Z. Review on Shot Peening Strengthening Mechanism of Metallic Materials. *China Surf. Eng.* **2012**, *25*, 1–9. (In Chinese)
24. Wang, C.; Jiang, C.; Ji, V. Thermal stability of residual stresses and work hardening of shot peened tungsten cemented carbide. *J. Mater. Process. Techonl.* **2017**, *240*, 98–103. [CrossRef]
25. Bagherifard, S.; Ghelichi, R.; Guagliano, M. On the shot peening surface coverage and its assessment by means of finite element simulation: A critical review and some original developments. *Appl. Surf. Sci.* **2012**, *259*, 186–194. [CrossRef]
26. Lin, Q.J.; Liu, H.J.; Zhu, C.C.; Parker, R.G. Investigation on the effect of shot peening coverage on the surface integrity. *Appl. Surf. Sci.* **2019**, *489*, 66–72. [CrossRef]
27. Trsko, L.; Guagliano, M.; Lukac, P.; Bokuvka, O.; Novy, F. Effects of severe shot peening on the surface state of AW 7075 Al alloy. *Kovove. Mater. Met. Mater.* **2015**, *53*, 239–243. [CrossRef]
28. John, M.; Kalvala, P.R.; Misra, M.; Menezes, P.L. Peening techniques for surface modification: Processes, properties, and applications. *Materials* **2021**, *14*, 3841. [CrossRef]
29. Cho, K.T.; Song, K.; Oh, S.H.; Lee, Y.K.; Lim, K.M.; Lee, W.B. Surface hardening of aluminum alloy by shot peening treatment with Zn based ball. *Mater. Sci. Eng. A.* **2012**, *543*, 44–49. [CrossRef]
30. Kikuchi, S.; Nakamura, Y.; Nambu, K.; Ando, M. Effect of shot peening using ultra-fine particles on fatigue properties of 5056 aluminum alloy under rotating bending. *Mater. Sci. Eng. A.* **2016**, *652*, 279–286. [CrossRef]
31. Valiev, R.Z.; Estrin, Y.; Horita, Z.; Langdon, T.G.; Zehetbauer, M.J.; Zhu, Y. Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation: Ten Years Later. *JOM* **2016**, *68*, 1216–1226. [CrossRef]
32. Gao, Y.K.; Zhao, Z.Y. Surface Integrity of Gear and Development Trend of Anti-Fatigue Manufacturing Technology. *Heat. Treat. Met.* **2014**, *39*, 1–6. (In Chinese)
33. Niu, J.T.; Liu, Z.Q.; Wang, B.; Hua, Y.; Wang, G.J. Effect of machining-induced surface integrity on the corrosion behavior of Al–Li alloy 2A97 in sodium chloride solution. *Mater. Corros.* **2019**, *70*, 259–267. [CrossRef]
34. Niu, J.T.; Liu, Z.Q.; Wang, G.J. Comparative Study on Electrochemical Behavior of Al-Li Alloy 2A97 Machined Surfaces in Sodium Chloride Solution. *IEEE. Access.* **2019**, *7*, 134198–134205. [CrossRef]
35. Clauer, A.H. Laser shock peening, the path to production. *Metals* **2019**, *9*, 626. [CrossRef]
36. Gujba, A.K.; Medraj, M. Laser peening process and its impact on materials properties in comparison with shot peening and ultrasonic impact peening. *Materials* **2014**, *7*, 7925–7974. [CrossRef]
37. Marteau, J.; Bigerelle, M.; Mazeran, P.E.; Bouviera, S. Relation between roughness and processing conditions of AISI 316L stainless steel treated by ultrasonic shot peening. *Tribol. Int.* **2015**, *82*, 319–329. [CrossRef]
38. Ding, X.; Kang, Y.; Li, D.; Wang, X.C.; Zeng, D.P. Experimental investigation on surface quality processed by self-excited oscillation pulsed waterjet peening. *Materials* **2017**, *10*, 989. [CrossRef]
39. Yang, L.; Huang, G.Z.; Zhou, B.; Zhang, C.; Bai, D. Effect of shot peening on corrosion resistance of 6082 aluminum alloy. *Heat Treat. Met.* **2019**, *44*, 161–166. (in Chinese)
40. Nam, Y.S.; Jeong, Y.I.; Shin, B.C.; Byun, J.H. Enhancing surface layer properties of an aircraft aluminum alloy by shot peening using response surface methodology. *Mater. Des.* **2015**, *83*, 566–576. [CrossRef]

41. Gao, Y.K.; Wu, X.R. Experimental investigation and fatigue life prediction for 7475-T7351 aluminum alloy with and without shot peening-induced residual stresses. *Acta Mater.* **2011**, *59*, 3737–3747. [CrossRef]
42. González, J.; Bagherifard, S.; Guagliano, M.; Pariente, I.F. Influence of different shot peening treatments on surface state and fatigue behavior of al 6063 alloy. *Eng. Fract. Mech.* **2017**, *185*, 72–81. [CrossRef]
43. Win, K.N.; Quang, T.P.; Lee, B.D. Study on hardness and wear resistance of shot peened AA7075-T6 aluminum alloy. *Eng. Res. Express.* **2021**, *3*, 015031.
44. Pandey, V.; Chattopadhyay, K.; Srinivas, S.N.C.; Singh, V. Role of ultrasonic shot peening on low cycle fatigue behavior of 7075 aluminum alloy. *Int. J. Fatigue* **2017**, *103*, 426–435. [CrossRef]
45. Gao, Z.; Liao, K.; Chen, J. Surface Characteristic Function of Al Alloy after Shot Peening. *Coatings* **2021**, *11*, 160. [CrossRef]
46. Zhang, J.R.; Chang, X.Q.; Sheng, X.F.; Cheng, Z.C.; Xia, Q.X. Effect of shot peening on surface roughness of 7075 aluminum alloy. *Light. Alloy. Manuf. Technol.* **2014**, *42*, 54–59. (In Chinese)
47. Sheng, X.; Xia, Q.; Cheng, X.; Lin, L.S. Residual stress field induced by shot peening based on random-shots for 7075 aluminum alloy. *T. Nonferr. Metal. Soc.* **2012**, *22*, 261–267. (In Chinese) [CrossRef]
48. Liu, C.W.; Liao, K.; Chen, J.W.; Li, L.J. Simulation and Experimental Study on Effect of Shot Peening on Surface Roughness of 7075-T651 Aluminum Alloy. *Trans. Mater. Heat Treat.* **2021**, *42*, 172–180. (In Chinese)
49. Trško, L.; Guagliano, M.; Bokůvka, O.; Nový, F.; Jambor, M.; Florková, Z. Influence of severe shot peening on the surface state and ultra-high-cycle fatigue behavior of an AW 7075 aluminum alloy. *J. Mater. Eng. Perform.* **2017**, *26*, 2784–2797. [CrossRef]
50. Wang, Y.J.; Sun, B.L.; Zhang, W.; Gao, G.Q.; Qiao, M.J. Numerical simulation and experiment of shot peening strengthening of al-li alloy. *J. Aerosp. Power* **2015**, *30*, 595–602. (In Chinese)
51. Miao, H.Y.; Mann, P.; Gariépy, A.; Lévesque, M.; Chromik, R.R. Residual stress near single shot peening impingements determined by nanoindentation and numerical simulations. *J. Mater. Sci.* **2015**, *50*, 2284–2297.
52. Lawerenz, M.D. Shot Peening and its Effect on Gearing. *SAE. Tech. Pap.* **1984**, *93*, 1023–1033.
53. Zhao, Y.X.; Liu, D.X.; Guan, Y.Y.; Cheng, S.M.; Du, D.X.; Li, P.; Liu, H.B.; Wang, Y.H. Influence of ceramic peening on fatigue properties of 2024HDT aluminum alloy. *Ordnance. Mater. Sci. Eng.* **2014**, *37*, 15–20. (In Chinese)
54. Zeng, W.; Yang, J. Quantitative representation of mechanical behaviour of the surface hardening layer in shot-peened nickel-based superalloy. *Materials* **2020**, *13*, 1437. [CrossRef]
55. Li, B. Comparative Experimental study on different Surface strengthening processes of 7075 Aluminum Alloy. *Light. Alloy. Process. Technol.* **2016**, *44*, 36–40. (In Chinese)
56. Zhu, L.H.; Guan, Y.J.; Wang, Z.S.; Zheng, H.Y.; Lin, J.; Zhai, J.Q.; Xie, Z.D. Influence of Surface Nanocrystallization and Partial Amorphization Induced by Ultrasonic Shot Peening on Surface Properties of 7075 Aluminum Alloy. *J. Mater. Eng. Perform.* **2020**, *29*, 7693–7709. [CrossRef]
57. Avcu, Y.Y.; Gönül, B.; Yetik, O.; Sönmez, F.; Cengiz, A.; Guney, M.; Avcu, E. Modification of Surface and Subsurface Properties of AA1050 Alloy by Shot Peening. *Materials* **2021**, *14*, 6575. [CrossRef]
58. Li, L.J.; Li, Y.S. Effect of shot peening duration on mechanical properties and microstructure of 5052 al-mg alloy. *Hot Working Technol.* **2018**, *47*, 93–96. (In Chinese)
59. Tao, X.F.; Gao, Y.K.; Kang, J.M.; Wang, Y.W. Softening effects induced by shot peening for an aluminum-lithium alloy. *Metall. Mater. Trans. A* **2020**, *51*, 410–418. [CrossRef]
60. Yang, F.B.; He, Y.F.; Li, D.Q.; Zhu, Q. Salt Spray Corrosion Resistance of SSM319s Aluminum Alloy with Surface Blast Treatment. *Rare. Met.* **2014**, *38*, 941–947. (In Chinese)
61. Ye, Z.Y.; Liu, D.X.; Wu, J. Effect of Shot peening and Stress Factors on Denudation Behavior of 2E12-T3 Aluminum Alloy. *Corros. Sci. Prot. Technol.* **2013**, *25*, 445–450. (In Chinese)
62. Pandey, V.; Singh, J.K.; Chattopadhyay, K.; Santhi Srinivas, N.C.; Singh, V. Optimization of USSP duration for enhanced corrosion resistance of AA7075. *Ultrasonics* **2019**, *91*, 180–192. [CrossRef] [PubMed]
63. Sun, Q.Q.; Liu, X.T.; Han, Q.Y.; Li, J.; Xu, R.; Zhao, K.J. A comparison of AA2024 and AA7150 subjected to ultrasonic shot peening: Microstructure, surface segregation and corrosion. *Surf. Coat. Technol.* **2018**, *337*, 552–560. [CrossRef]
64. Sun, Q.Q.; Han, Q.Y.; Wang, S.; Xu, R. Microstructure, corrosion behaviour and thermal stability of AA 7150 after ultrasonic shot peening. *Surf. Coat. Technol.* **2020**, *398*, 126127. [CrossRef]
65. Lee, H.S.; Kim, D.S.; Jung, J.S.; Pyoun, Y.S.; Shin, K. Influence of peening on the corrosion properties of AISI 304 stainless steel. *Corros. Sci.* **2009**, *51*, 2826–2830. [CrossRef]
66. Hadzima, B.; Bukovina, M.; Dolezal, P. Shot peening influence on corrosion resistance of AE21 magnesium alloy. *Mater. Eng.* **2010**, *17*, 14–19.
67. He, W.; Wang, Y.N.; Liu, J.S.; Wang, Y.L.; Tan, J.G.; Gao, J. Effect of rotating shot peening on stress corrosion resistance of 7b04-t6 aluminum alloy. *J. Aeronaut. Mater.* **2020**, *40*, 52–58. (In Chinese)
68. Mhaede, M. Influence of surface treatments on surface layer properties, fatigue and corrosion fatigue performance of AA7075 T73. *Mater. Design.* **2012**, *41*, 61–66. [CrossRef]
69. Pandey, V.; Singh, J.K.; Chattopadhyay, K. Influence of ultrasonic shot peening on corrosion behavior of 7075 aluminum alloy. *J. Aalloy. Compd.* **2017**, *723*, 826–840. [CrossRef]
70. Trdan, U.; Grum, J. Evaluation of corrosion resistance of AA6082-T651 aluminium alloy after laser shock peening by means of cyclic polarisation and ElS methods. *Corros. Sci.* **2012**, *59*, 324–333. [CrossRef]

71. Lv, S.L.; Cu, Y.; Zhang, W.; Tong, X.Y.; Srivatsan, T.S.; Gao, X.S. Influence of shot peening on failure of an aluminum alloy exposed to aggressive aqueous environments. *J. Mater. Eng. Perform.* **2013**, *22*, 1735–1743. [CrossRef]
72. Wang, J.T.; Zhang, Y.K.; Chen, J.F.; Zhou, J.Y.; Lu, Y.L.; Zhang, C.Y. Effect of High Intensity Laser Shock on electrochemical Corrosion Behavior of Plasma Arc Welding joints of 7075 Aluminum Alloy. *Chin. J. Lasers.* **2015**, *12*, 106–115. (In Chinese)
73. Abdulstaar, M.; Mhaede, M.; Wollmann, M.; Wagner, L. Investigating the effects of bulk and surface severe plastic deformation on the fatigue, corrosion behaviour and corrosion fatigue of AA5083. *Surf. Coat. Tech.* **2014**, *254*, 244–251. [CrossRef]
74. Fern, I. TEM evaluation of steel nanocrystalline surfaces obtained by severe shot peening. *Surf. Coat. Technol.* **2021**, *418*, 127238.
75. Bagheri, S.; Guagliano, M. Review of shot peening processes to obtain nanocrystalline surfaces in metal alloys. *Surf. Eng.* **2009**, *25*, 3–14. [CrossRef]
76. Su, L.; Lu, C.; Li, H.; Deng, G.; Tieu, K. Investigation of ultrafine grained AA1050 fabricated by accumulative roll bonding. *J. Mater. Sci. Eng. A.* **2014**, *614*, 148–155. [CrossRef]
77. Bagherifard, S. Enhancing the structural performance of lightweight metals by shot peening. *Adv. Eng. Mater.* **2019**, *21*, 1801140. [CrossRef]
78. Amini, S.; Kariman, S.A.; Teimouri, R. The effects of ultrasonic peening on chemical corrosion behavior of aluminum 7075. *Int. J. Adv. Manuf. Tech.* **2017**, *91*, 1091–1102. [CrossRef]
79. Zhou, K.; Yang, Y. Effect of laser shot peening on microstructure and stress corrosion resistance of 2195 Al-Li alloy. *Al. Fab.* **2019**, *2*, 10–14. (In Chinese)
80. Lv, Y.T.; Zhao, B.J.; Zhang, H.B.; Su, C.J.; Nie, B.; Wang, R.; Cao, L.M.; Lyu, F.Y. Improving Corrosion Resistance Properties of Nickel-Aluminum Bronze (NAB) Alloys via Shot Peening Treatment. *Mater. Trans.* **2019**, *60*, 1629–1637. [CrossRef]
81. Niu, J.T.; Liu, Z.Q.; Qiao, Y.; Wang, X.Y.; Chen, H.T. Novel combination of indicators to compare the corrosion behaviors of Al, Al–Li alloy 2A97, and other Al alloys. *Mater. Corros.* **2022**, *73*, 171–179. [CrossRef]
82. Deng, Y.H.; Liu, J.; Qiao, Y.; Niu, J.T. Comparative investigations on the electrochemical behaviors among Al and aluminum alloys. *Mater. Res. Express.* **2020**, *7*, 116510. [CrossRef]
83. Prakash, N.A.; Gnanamoorthy, R.; Kamaraj, M. Surface nanocrystallization of aluminium alloy by controlled ball impact technique. *Surf. Coat. Tech.* **2012**, *210*, 78–89. [CrossRef]
84. Chen, J.S.; Desai, D.A.; Heyns, S.P.; Pietra, F. Literature review of numerical simulation and optimisation of the shot peening process. *Adv. Mech. Eng.* **2019**, *11*, 1–19. [CrossRef]