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Review

State of the Art and Perspectives on Surface-Strengthening Process and Associated Mechanisms by Shot Peening

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Abstract: Shot peening is a surface-strengthening process that is widely used in various industries, such as aerospace, automotive, and biomedical engineering. The process involves the impact of small, spherical media, called shots, onto the surface of a material, resulting in residual compressive stress and improved surface properties. This review aims to provide an overview of the state of the art and perspectives on surface strengthening by shot peening. The review covers various aspects of shot peening, including process parameters, shot materials, and quality control techniques. The advantages and limitations of shot peening in comparison to other surface-strengthening techniques are also discussed. The findings of this review indicate that shot peening is a versatile and effective surface-strengthening technique with numerous applications, and further research is needed to fully realize its potential. In conclusion, this review provides insights into the current status and future perspectives on surface strengthening by shot peening, and it is expected to be useful for researchers, engineers, and practitioners in the field of material science and engineering.

Keywords: shot peening technology; surface-strengthening process; shot peening coverage; surface-strengthening mechanisms

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1. Introduction

The machinery industry has seen rapid development in recent years, leading to increased demands for improved performance in mechanical parts in various industries such as defense, transportation, power energy, and engineering machinery [1–5]. Fatigue failure and wear failure, which account for 80% of all mechanical part failures, usually originate from the surface [6–10]. Thus, surface-strengthening technologies are required to improve the quality of mechanical parts and enhance their resistance to fatigue and wear, resulting in a longer service life [11–15].

Surface strengthening is a technique aimed at altering the surface integrity of components by subjecting them to external force or heat treatment, without the addition of external materials. This method is widely used to enhance the properties of components, such as fatigue, wear, and stress corrosion resistance. In general, the surface strengthening is always associated with the surface phase transformation, which can be induced by the surface deformation caused by the mechanical impacting on target surface, such as shot peening technology [16,17], and by the surface quenching due to the heat effect [18]. The shot peening process involves the acceleration of projectiles which are then directed at the surface of the workpiece, creating a layer of residual compressive stress, thereby increasing the service life of the component [19]. Figure 1 illustrates the shot peening process. Shot peening is simpler, more cost effective, and is not limited by the shape or size of the workpiece compared to surface rolling or surface quenching. The strengthening speed is quick, and the results are significant. It is therefore not surprising that shot peening has gained widespread use in industries such as aerospace and automotive, due to its ability to increase the resistance of components to fatigue failure and wear failure.

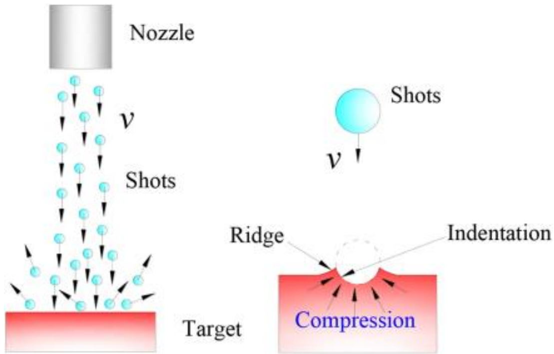


Figure 1. Schematic representation of the shot peening process [20].

As a popular choice for wear-resistant materials in various industries, steel has been used to create various mechanical components. ZGMn13 high manganese steel, for instance, has exceptional wear resistance and is widely utilized in industries such as automobile, railway, electric power, and mining due to its high performance and low production costs [21]. However, its wear resistance is only evident under conditions of high stress and strong impact. Additionally, its low yield strength makes it susceptible to plastic deformation during use, leading to increased wear. Research has shown that grain refinement, achieved through multiple modification and aging treatment, can enhance ZGMn13 high manganese steel's performance [22]. Alternatively, the addition of elements such as Cr and Mo through alloying and heat treatment can improve its hardness and wear resistance. However, these above-mentioned surface-strengthening technologies are either chemical or thermal based method that need to accurately control the concentration of the added elemental alloying or the heat treatment temperature. Shot peening technology is a promising technique for surface strengthening, and it is based on the mechanical impacting on the target surface and hence inducing the grain refinement, which is easy to operate and low at cost. Thus, it is necessary to conduct a review on the state of the art and perspectives of surface strengthening through shot peening.

Previous review work on the shot peening technology has been conducted by many researchers. The creation of nanocrystallized layer by the shot peening of metal alloys has been reviewed by Bagheri et al. [23], and the available microstructural characteristics of nanocrystal thin layers obtained with different processes were presented. Moreover, Bagherifard [24] also conducted a review on enhancing the structural performance of lightweight metals by shot peening, and emergent applications and the existing challenges were highlighted in this work, which could guide the future research directions in this field. Świetlicki et al. [25] presented a short review on the effects of shot peening and cavitation peening on properties of surface layer of metallic materials, and it suggested that there was a need to investigate the effects of peening, especially cavitation peening and hybrid peening, on the anti-wear and corrosion performance of additively manufactured metallic materials. Although these review works have been contributed to the development of the shot peening technology, some of the underlying mechanisms of surface strengthening and its relation with respect to the shot peening process, such as the shot peening coverage, still need to be properly discussed and concluded.

Therefore, in this review paper, the classification of the shot peening technology and their applications will be firstly discussed, and the related numerical study on this process will be analyzed to emphasize its significance. Then, the surface-strengthening mechanisms by the shot peening process and the effect of processing parameters, such as the shot peening coverage, on the shot peening performance will be comprehensively explored, and finally, the perspectives of the shot peening technology for the surface strengthen will be concluded to facilitate the future work.

2. Development and Classification of the Shot Peening Technology

The roots of shot peening technology can be traced back to the late 19th century sandblasting technology. Tighman's invention of vacuum pressurization technology in 1870, which used air pressure to propel abrasive particles, marked the beginning of sandblasting technology. In 1908, the advent of chilled steel shots led to the development of shot peening as a metal surface-strengthening process. In 1929, Zimmerli et al. used shot peening on spring steel and observed significant improvement in its performance. By the 1930s, shot peening was applied in automobile manufacturing and expanded to the aviation industry in the 1960s to prevent fatigue failure of aircraft parts. In the 1980s, the application of shot peening continued to increase and it has since been widely used for surface strengthening of various parts [26]. With advancements in technology, research on shot peening and its underlying mechanism has deepened, leading to improvements in the precision and automation of shot peening equipment and driving its rapid development.

Currently, various research studies have been conducted to examine the effects of shot peening on friction and wear resistance, fatigue resistance, and surface properties of treated materials [27–29]. With advancements in technology, in addition to conventional shot peening, various emerging shot peening methods have been proposed, including laser shock peening, micro-particle shot peening, ultrasonic shot peening, and high pressure water jet shot peening [26]. These techniques will be analyzed in further detail.

2.1. Laser Shock Peening

Laser shock peening (LSP) is a technology that impacts the workpiece using a laser beam rather than a projectile flow. The target surface absorbs laser energy, creating a high-temperature, high-pressure plasma. The plasma expands and generates a high-pressure shock wave transmitted to the surface layer. If the shock wave's maximum pressure is greater than the workpiece's dynamic yield strength, residual compressive stress is produced on the workpiece surface, thus improving its fatigue performance. Figure 2 illustrates the laser shock peening process [30]. Compared to conventional shot peening, laser shock peening generates a residual compressive stress layer that can reach over 1 mm, 2–5 times deeper than traditional shot peening. This residual stress can reduce the average stress, decrease fatigue crack propagation speed, and is considered advantageous due to its strong strengthening effect, good control, and broad application range. However, the high cost of laser shock peening equipment limits its use [31,32].

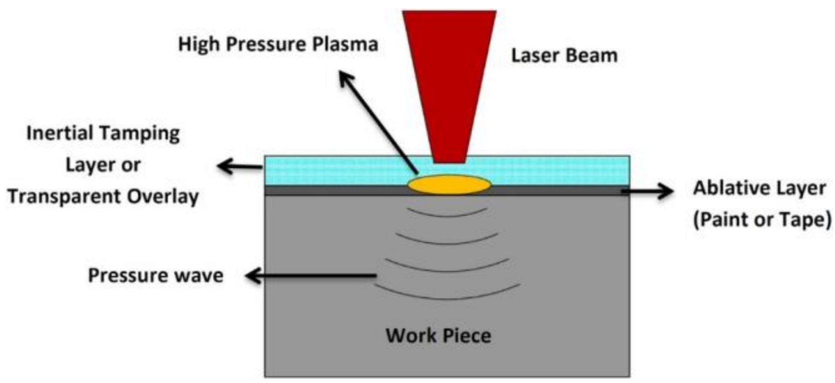


Figure 2. Schematic representation of the laser shock peening process [30].

2.2. Micro-Particle Shot Peening

Micro-particle shot peening (MSP) is a new process that involves impacting the work-piece surface with high-speed steel shot or ceramic powder in the size range of 0.04–0.2 mm. This process is faster than conventional shot peening and results in unique surface modification abilities [33]. The smaller size of the micro-particles and faster shot peening speed facilitates unique surface modification abilities. This results in an improved hardness of the workpiece surface and reduced surface damage, but a shallower residual compressive stress layer compared to traditional shot peening. Micro-particle shot peening allows the workpiece surface to be impacted by numerous micro-particles in a short period of time, resulting in plastic deformation and refinement of the structure, improved surface hardness, and reduced surface damage [34]. However, the depth of residual compressive stress generated on the workpiece surface is shallow, limiting its applications to some extent [35].

2.3. High Pressure Water Jet Shot Peening

The principle of high pressure water jet shot peening (WJSP) is the use of a high pressure water jet to produce plastic deformation on the workpiece's surface, resulting in a residual compressive stress layer that improves the workpiece's fatigue performance [36]. This process has advantages over conventional shot peening including reduced stress concentration, minimal increase in machined surface roughness, and easier processing of narrow and small parts. It is also more efficient and environmentally friendly, with good development prospects [37].

2.4. Ultrasonic Shot Peening

Ultrasonic shot peening (USP) uses high-power ultrasound, delivered by a transducer and horn, to drive metal or ceramic projectiles to impact the workpiece for shot peening [38]. The principle is shown in Figure 3 [39]. This process results in a deeper strengthening layer and larger residual compressive stress on the workpiece surface compared to traditional shot peening, leading to a better strengthening effect. Its small equipment size and relatively low cost make it useful in industries such as automotive manufacturing and aerospace [40].

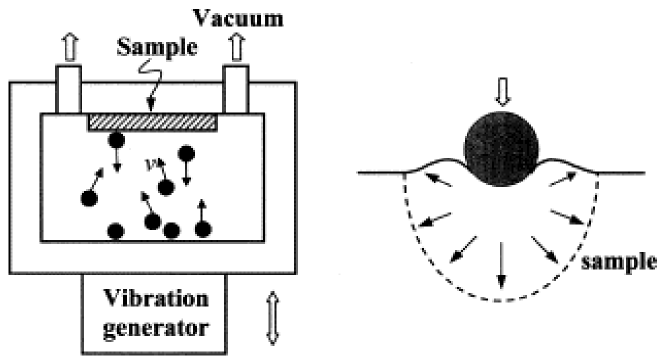


Figure 3. Schematic representation of the ultrasonic shot peening process [39].

The characteristics and new advances of the different surface-strengthening methods as mentioned above, including LSP, MSP, WJSP, and USP, have been compared as shown in Table 1. Furthermore, the improvement in hardness and residual stress by using LSP, MSP, WJSP, and USP compared with non-peened target materials has been properly summarized as shown in Table 2.

In conclusion, these alternative shot peening strengthening methods have unique benefits compared to conventional shot peening but require further investigation and refinement in their processes before they can be widely adopted. Traditional shot peening, while widely utilized, has a more established process and technology. Further exploration into the mechanics behind traditional shot peening is needed.

Table 1. Comparison of different surface-strengthening methods [26].

Surface-Strengthening Methods	Characteristics	New Advances
LSP	Deeper surface-strengthening layer; more stable energy; lower roughness; better thermal stability. However, point-by-point strengthening; expensive equipment; more complex operations.	LSP plus MSP; LSP coupling low temperature; LSP coupling high temperature.
MSP	Larger surface-strengthening layer; higher maturity, stronger applicability and most widely application; simpler operation; lower cost and higher efficiency. However, significantly increased roughness.	MSP plus vibration finishing; pre-tensile stress MSP; secondary MSP; in situ warm MSP; wet MSP.
WJSP	Better surface roughness; easier processing of narrow and small parts.	Cavitation peening by WJSP.
USP	Shallower bombardment indentations; more environmentally friendly; lower cost and higher efficiency. Limited by part shape and sealed chamber.	Ultrasonic hammering method.

Table 2. Improvement of hardness and residual stress by using LSP, MSP, WJSP, and USP comparing with non-peened target materials.

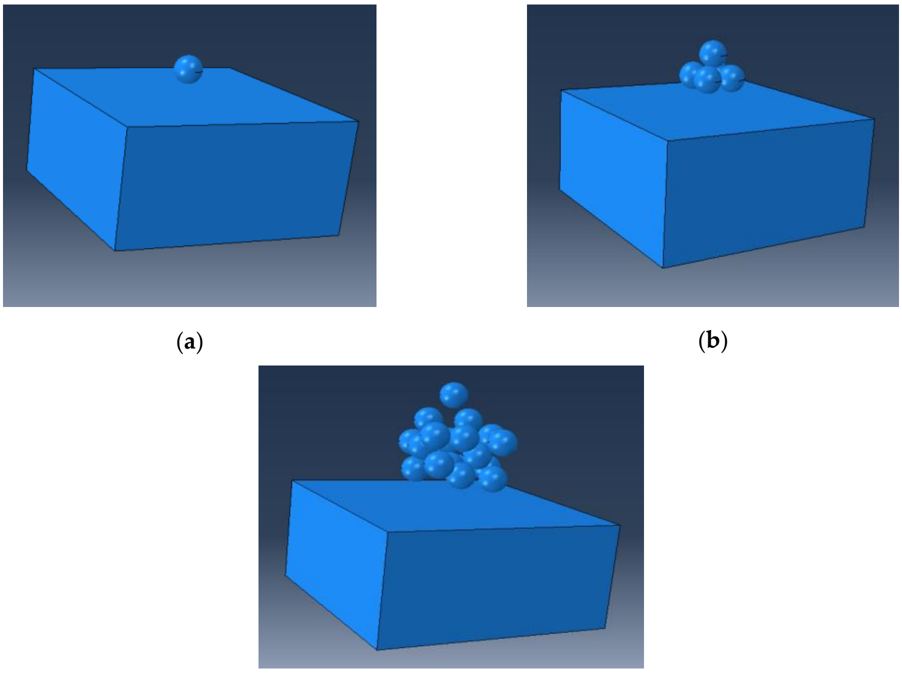
Materials	Vickers Hardness					Residual Stress, MPa					Reference
	Non-Peened	LSP	MSP	WJSP	USP	Non-Peened	LSP	MSP	WJSP	USP	
Titanium alloy Ti6Al4V	344	338	386	367		−220	−450	−348	−648		[41]
Aluminum alloy A2017	130	280	180	160		20	−211	−248	−297		[42]
Aluminum alloy A5005	55				75						[43]
Nickel alloy 200	116				154						[44]
Carbon steel AISI1045						−40				−200	[45]

3. Numerical Investigation of the Shot Peening Process

The mechanism of shot peening enhancement of workpieces is highly complex, and the selection and combination of shot peening process parameters will directly impact the shot peening effect on the workpieces. Currently, it is difficult to explain the relationship between the various process parameters and the shot peening effect in the shot peening enhancement process through an accurate mathematical model, and can only be studied through a large number of shot peening experiments. However, shot peening experiments are not only time consuming, but also the experience of the experimenter can affect the shot peening effect. In addition, the cost of residual stress detection of the workpiece after shot peening enhancement is relatively high, and these issues will all impact the development of the shot peening enhancement process. Thus, numerical simulation seems to be a powerful tool to address these issues and has been extensively used in the engineering to explore the associated underlying mechanisms [46–53].

Finite Element Method (FEM) is an important technique in computational mechanics; it is a numerical technique that seeks to approximate the solution of partial differential equations by dividing complex problems into smaller elements that can be solved mutually [54]. The method can be used to establish a numerical model that matches the actual shot peening situation, to simulate the dynamic process accurately, to analyze the residual compressive stress field and surface roughness of the target material, and to explore the shot peening enhancement mechanism [8,17]. Through numerical simulation, time and cost can be saved, and the best combination of shot peening process parameters can be quickly determined, providing guidance for further shot peening experiments. Currently, there are a large number of numerical simulation studies on shot peening enhancement, both domestically and abroad [55–57].

When establishing a shot peening numerical model, the distribution of the position of the shot above the target material is a problem that must be taken into consideration. In previous shot peening numerical models, three common distributions of shot position are shown in Figure 4. The single shot model has low computational demands and can save computation time, and it can be used to analyze the effects of various shot peening process parameters and combinations on the shot peening effect. Meguid et al. [58] established a single shot model to study the changes in residual stress size and stress layer depth in the target material under different shot speeds, sizes, and shapes. Kim et al. [59] studied the formation of residual stress in the target material after shot peening by establishing a single shot model. Hong et al. [60] established a numerical model of a single shot impact on the target material during the shot peening process, and they analyzed the changes in residual compression stress in the target material under different shot speeds and impact angles. Liu [61] analyzed the effects of shot diameter, shot speed, and shot angle on residual stress in the workpiece under a single shot model. Wang [62] used LS-DYNA to establish a single shot model and design an orthogonal experiment to analyze the residual compression stress field in the target material under different combinations of shot peening process parameters, ultimately obtaining the optimal combination of shot peening process parameters.



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

Figure 4. Numerical model of the shot peening process: (**a**) single shot, (**b**) regular array shot, (**c**) random shot.

The actual shot peening process involves multiple shot impacts on the target surface, and the single shot model cannot reflect the influence between shots, nor can it study the changes in residual stress field of the target material under different shot coverage. Therefore, Majzoobi et al. [63] established a numerical model with multiple shots distributed in an axisymmetrical manner to study the trend of residual stress changes under different shot velocity and coverage. Li et al. [64] established an enhanced model with 11 shots tightly arranged, representing 100% shot coverage, to analyze the significant changes in residual stress field of the target material under 100% shot coverage through numerical simulation.

Zhang et al. [65] used the finite element method to establish a regular distributed multiple shot peening model and analyzed the influence of shot velocity, continuous impact, and secondary impact on residual compressive stress field of the target. However, these numerical models have predetermined positions of shots impacting the target, while in actual shot peening processes, shots randomly impact the target, so these numerical models still have certain shortcomings and cannot truly simulate the dynamic process of shot peening. Therefore, Miao et al. [66] combined the MATLAB program with ANSYS preprocessor to establish a numerical model with multiple randomly distributed shots. Li et al. [67] used python programming language to develop the finite element software ABAQUS and established a numerical model with randomly located shots, studying the relationship between shot peening process parameters and residual stress of the shot-peened workpiece. Wang et al. [68] based on the ABAQUS secondary development, established a numerical model with multiple shots that have random distribution and shot number determined by shot coverage, and analyzed the trend of surface roughness and residual stress changes of TC4 titanium alloy under different shot peening conditions. Sheng et al. [69] developed a subroutine for randomly generating the coordinates of shot peening using the Python programming language. By using this program, a numerical model for random shot peening was established, and the effects of different shot peening process parameters on the surface roughness of the workpiece and the energy conversion during shot impact were studied.

To summarize, the single-particle model has low computational requirements and can save computation time. It can be used to analyze the effects of different shot peening process parameters and combinations on the shot peening effect; for instance, the single-particle shot peening numerical model can be used to analyze the effects of particle diameter, particle velocity, and impact angle on the residual compressive stress field of the target material in order to determine the optimal process parameter combination. The random particle model can truly reflect the initial state of particle position in the actual shot peening process, and compared to the regular arrangement particle model, it can improve the accuracy of the shot peening numerical simulation results.

4. Fundamental of the Traditional Shot Peening Technology

4.1. Shot Peening Process Parameters

In practical applications, the main parameters affecting the final shot peening effect on a workpiece are the size and material of the shot, impact angle, shot blasting pressure, distance between the nozzle and the workpiece, and coverage rate of shot peening. Among these parameters, the impact angle, shot blasting pressure, and distance between the nozzle and the workpiece can be controlled by the shot peening intensity. Hence, the critical parameters that need to be strictly controlled are the size and material of the shot, shot peening intensity, and coverage rate of shot peening [70].

In order to avoid unnecessary scratches on the workpiece surface and stress concentration during shot peening, the shot shape is generally spherical or cylindrical with smooth surface and no sharp edges. Currently, commonly used shot types in shot peening include cast steel shot, wire-cut shot, ceramic shot, and glass shot, and the use of different types of shots has a significant impact on the final processing effect of the workpiece. The scope of application of different shot types is given in Table 3.

The shot peening intensity represents the ability of a shot peening beam flow to introduce residual compressive stress into the workpiece surface. Under constant other process parameters, as the shot peening intensity increases, the thickness of the residual compressive stress layer will also increase. Shot peening intensity can be determined through the results of shot peening on standard Almen specimens [71,72]. There are three types of standard Almen specimens: N specimens, A specimens, and C specimens. All three specimens have the same length and width, but they differ in thickness, representing different strength levels. N specimens are suitable for low shot peening intensity applications, with an arc height value less than 0.15 mm. A specimens are suitable for medium shot peening intensity applications, with an arc height value between 0.15 and 0.6 mm. C specimens are suitable for high shot peening intensity applications, with an arc height value greater than 0.6 mm. By gradually increasing the time of shot peening on a set of standard Almen specimens, and then using an Almen testing instrument to test the arc height values of each specimen, a saturation curve is generated, as shown in Figure 5 [73]. The saturation degree in Figure 5 is a point on the saturation curve that satisfies a specific condition. The specific condition refers to the existence of another point on the saturation curve, where the shot peening time used is twice the saturation degree shot peening time, but the arc height value is only increased by 10% compared to the saturation degree arc height value. The shot peening intensity can be expressed by the arc height value on the saturation degree of the specimen.

Table 3. The scope of application of different shot types [61].

Shot Types	Scope of Application
Steel shot	Low hardness, typically in the range of 40 to 50 HRC, with good ductility of cast steel shots, high recovery rate, and suitable for moderate strength shot peening.
Wire-cut shot	High hardness, typically ranging from 55 to 62 HRC, good toughness, prone to breakage, and low recovery rate, suitable for high-intensity shot peening applications.
Ceramic shot	High hardness, generally ranging from 57 to 63 HRC, with the outstanding feature of high density and high hardness. Initially used for reinforcement of aircraft components. Due to the high strength of ceramic beads, with long lifespan and low cost, it has now been extended to the surface strengthening of colored metals such as titanium alloys and aluminum alloys.
Glass shot	Low hardness, suitable for materials such as titanium, aluminum, magnesium, and others that cannot be contaminated by ferrous materials. It can also be used as a secondary treatment after steel shot peening to eliminate ferrous contamination and reduce the roughness of the components.

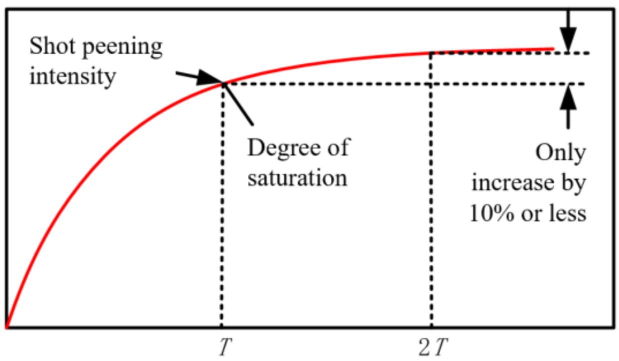


Figure 5. Saturation state curve [73].

The shot peening coverage refers to the percentage of the area of the pits on the workpiece after shot peening under a certain shot peening time, in relation to the area of the shot peening region of the workpiece. In actual shot peening strengthening processes, it is very difficult to accurately measure the shot peening coverage of the workpiece as 100%. Therefore, it is generally considered that when the shot peening coverage of the workpiece reaches 98%, full coverage, or 100% coverage, has been achieved. The shot peening time at which the shot peening coverage is 100% is designated as T. The shot peening time required for a 200% coverage would then be $2T$, and so on.

4.2. Shot Peening Strengthening Mechanisms

Shot peening is a commonly used surface-strengthening technique that belongs to a cold working process. The enhancement effect is apparent. Shot peening is carried out by shooting balls at a certain speed and angle onto the workpiece surface at room temperature. The continuous impacts of the balls on the workpiece surface cause repeated plastic deformation, leading to the generation of a residual stress layer with a certain depth on the workpiece surface. This improves the fatigue resistance of the workpiece and extends its service life, while also generating a hardening layer with a certain thickness, increasing the surface hardness of the workpiece [74]. After shot peening, the parts have higher surface hardness, which can enhance their ability to resist plastic deformation, and the residual stress on the surface layer can resist a portion of the tensile stress when the parts are pulled, thus enhancing the ability of the parts to resist fatigue and wear failure, and extending their service life [19]. For most metal materials, the residual stress distribution along the layer depth after shot peening is shown in Figure 6. As can be seen from Figure 6, after shot peening, the surface layer exhibits residual stress due to its resistance to plastic deformation, with the surface being compressive stress. As the depth from the surface increases, the compressive stress first increases, the maximum residual compressive stress occurs at the sub-surface of the workpiece, and then the compressive stress gradually decreases and transforms into tensile stress [17].

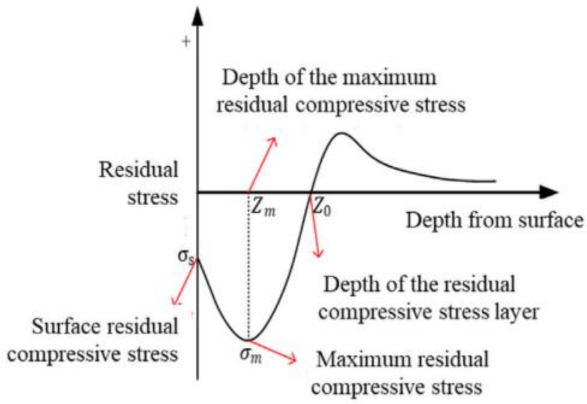


Figure 6. Evaluation of shot peening performance based on distribution of residual stress on target [17].

Furthermore, as shown in Figure 7, during shot peening, the continuous impact on the surface of the workpiece results in severe plastic deformation. Due to the compressive effect, elastic deformation regions within the workpiece form regions of permanent plastic deformation. Within the plastic deformation region, the microstructure of the workpiece changes and undergoes refinement of sub-grains and grain boundaries, accompanied by an increase in the density of dislocations as shown in Figure 7b [75].

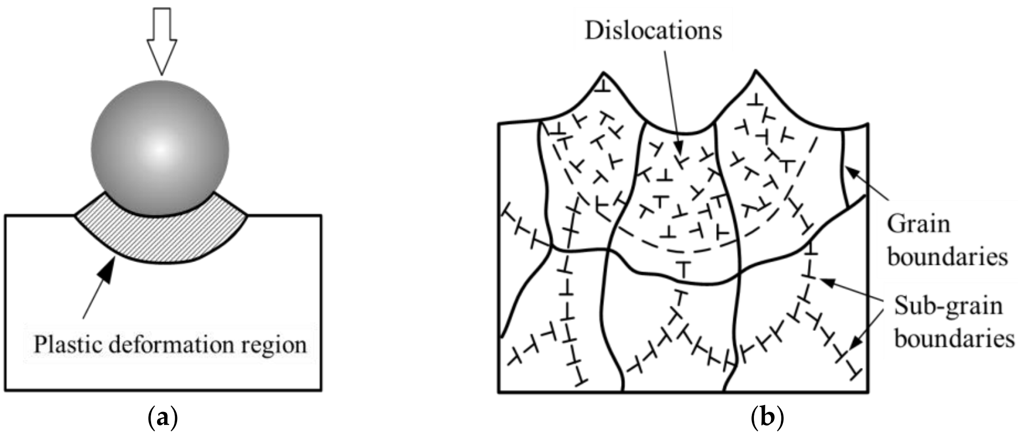


Figure 7. (**a**) Plastic deformation caused by ball impacting the workpiece surface, (**b**) microstructure of workpiece after ball impacting [75].

The mechanisms of shot peening can be divided into two types: stress-strengthening mechanism and microstructural-strengthening mechanism.

For the stress-strengthening mechanism, the surface of a component is a weak point and prone to fatigue cracking. After being subjected to shot peening, the residual compressive stress on the component surface can inhibit the formation of surface cracks and promote the transfer of fatigue cracks from the surface to the sub-surface layer [76]. Additionally, the residual compressive stress can increase the required external cyclic stress to produce fatigue cracks, thus enhancing the fatigue strength of the component. The impact of residual compressive stress is more pronounced on components with existing microcracks. In this case, when the component is subjected to tensile stress, the residual compressive stress on the surface can counteract some of the tensile stress, reducing the maximum cyclic stress applied to the component, improving the critical stress intensity factor for the initiation of microcracks, and reducing the rate of fatigue crack propagation, thus enhancing the fatigue strength of the component [77]. Furthermore, residual compressive stress can effectively suppress crystal sliding near the direction of maximum shear stress, improving the performance of the component.

For the microstructural-strengthening mechanism, shot peening is a process that uses a stream of projectiles to continuously and repeatedly impact the surface of a component. This causes severe plastic deformation in the surface layer, leading to an optimization of the microstructure and refinement of the grain structure, while also increasing the density of dislocations and microstrains, as shown in Figure 8, where the dislocation density of its surface material would increase rapidly, and therefore, abundant dislocation substructures were formed [78]. In some cases, such as austenitic steels, shot peening can also induce a martensitic transformation, resulting in transformation strengthening. This change in microstructure makes it difficult for the crystals in the deformed layer to slip, preventing sliding between the deformed layer and the internal interface. These effects can delay the time it takes for fatigue cracks to form on the surface of the component, thus improving its fatigue life and wear resistance [79]. Further, Figure 9 shows the EBSD characterizations of the ultrasonic shot peeing on dual-phase high entropy alloy with the peening duration of the 0 s, 60 s, 240 s, and 720 s, respectively, where the ultrasonic shot peeing treatment induces severe plastic deformation zone near the peening surface, significantly refining the grains and phases and hence strengthening the target surface [80].

In conclusion, the ability of shot peening to enhance the resistance of mechanical parts against fatigue and wear failure is mainly due to its ability to prevent the initiation and delay the propagation of cracks on the surface of the parts. It is generally believed that structural strengthening can prevent the initiation of cracks on the surface of mechanical parts, while stress strengthening can delay the further development of cracks. For materials with lower hardness and strength, structural strengthening plays a major role in enhancing the resistance of mechanical parts against fatigue and wear failure, while for materials with higher hardness and strength, stress strengthening plays a major role.

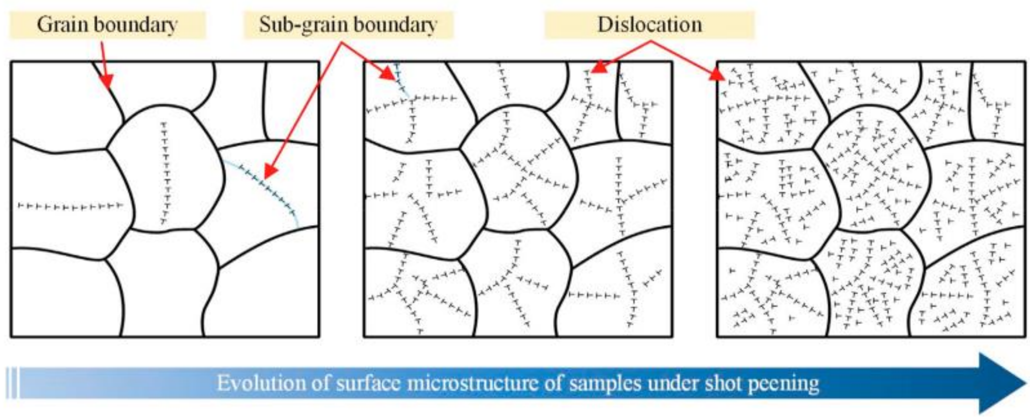


Figure 8. Schematic representation of microstructure evolution under shot peening [78].

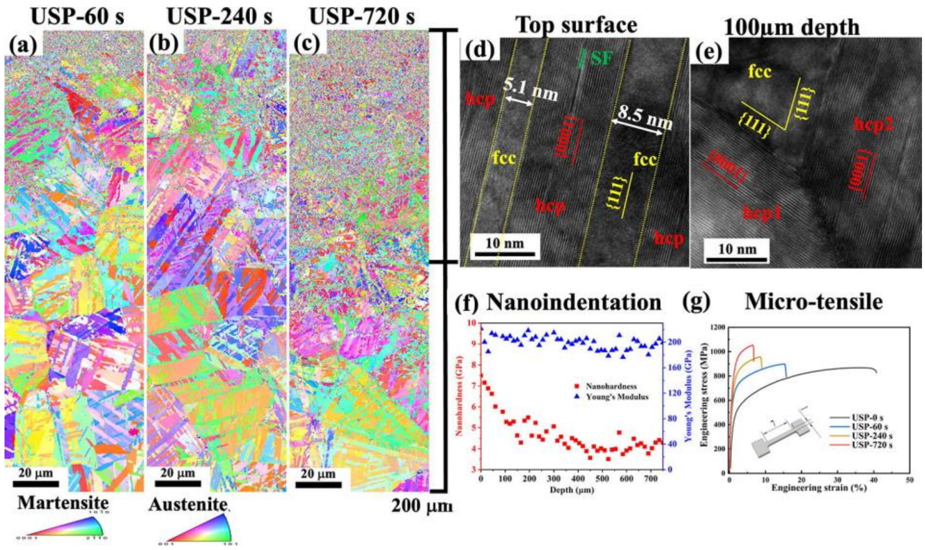


Figure 9. The microstructure refinement and mechanical strengthening of dual-phase high entropy alloy during ultrasonic shot peening [80].

4.3. Shot Peening Coverage

The significance of shot peening coverage in the shot peening strengthening process of workpieces is self-evident, and it will directly affect the final shot peening strengthening effect of the workpieces [81]. It is well known that insufficient shot peening coverage leads to insufficient coverage of residual compressive stress field on the surface of the workpieces, causing premature fatigue failure due to the inability to resist residual tensile stress during processing and use. However, shot peening coverage that is too high will also lead to premature fatigue failure due to excessive residual tensile stress and microcracks caused by excessive stress concentration and plastic deformation. Li et al. [82] conducted a study to analyze the fatigue characteristics of 300 M steel under different shot peening coverage levels and found that higher shot peening coverage does not necessarily mean better fatigue characteristics. Therefore, it is critical to find a reasonable shot peening coverage level in shot peening strengthening of workpieces, and one should not blindly pursue high shot peening coverage when selecting shot peening strengthening process parameters.

In the process of shot peening, the number of shot particles impacting the surface of the workpiece has a linear relationship with the peening time, with a longer peening time resulting in a larger number of shot particles impacting the surface [83]. However, shot particles randomly impact the surface of the workpiece, meaning that not every shot particle impacts a new location on the surface. Some may impact the same location as the previous particle, and a single location on the surface of the workpiece may be repeatedly impacted multiple times during the shot peening process. As a result, the relationship between the shot peening coverage and the corresponding peening time is not linear.

Figure 10 presents the experimental results of the relationship between the shot peening coverage rate and the time factor [84]. The time factor for one shot peening is 2, and the time factor for two shot peenings is double that of one shot peening, i.e., 4, and so on. From Figure 10, it can be seen that in the initial period, the growth rate of shot peening coverage rate is significant; however, as time goes on, the growth rate becomes slower, and the shot peening coverage rate reaches nearly 100% without much growth. From the data in the figure, the shot peening time required to increase the coverage rate from 80% to 100% is approximately double that required to increase the coverage rate from 0% to 80%, and the shot peening time required to increase the coverage rate from 90% to 100% is about 1.2 times that required to increase the coverage rate from 0% to 90%, and the shot peening time required to increase the coverage rate from 98% to 100% accounts for 30% of the total time required to increase the coverage rate from 0% to 100%. Hence, considering the shot peening coverage rate of 98% as full coverage in practical processing can greatly reduce the shot peening time and improve production efficiency.

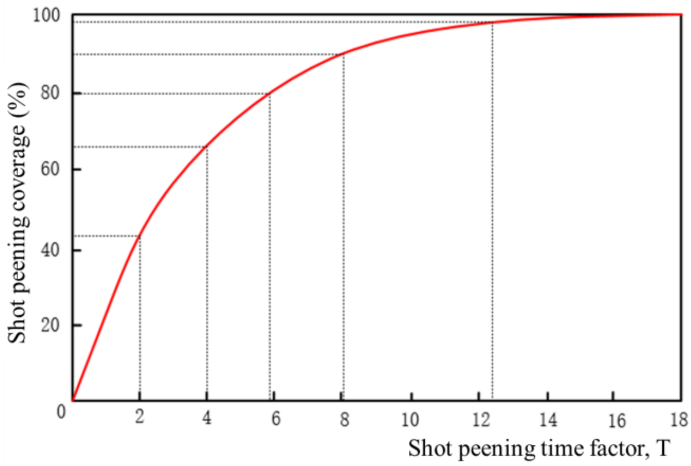


Figure 10. Experimental results of the relationship between shot peening coverage and shot peening time factor [84].

5. Perspectives of the Shot Peening Technology

The shot peening technology for surface strengthening has shown promising potential for a wide range of applications, and its development and utilization is expected to continue in the future. Below are a few key perspectives for the future of shot peening technology:

(1) New Materials: As new materials are developed and introduced into various industries, shot peening technology will need to adapt to meet the challenges of processing these materials. The use of new materials such as composites, ceramics, and metal matrix composites will require new shot peening strategies that can produce the desired surface characteristics and compressive stress profiles.

(2) Advanced Manufacturing Processes: The rise of advanced manufacturing processes such as additive manufacturing, laser cladding, and hybrid manufacturing will require new shot peening techniques to ensure the surface integrity of the manufactured components. Shot peening will need to be integrated into these advanced manufacturing processes to optimize their performance and enhance their properties.

(3) Digitalization: The digitalization of manufacturing processes is an ongoing trend that is likely to continue in the future. Shot peening technology can be integrated with digitalization to create a more efficient and data-driven process. The use of sensors, artificial intelligence, and machine learning algorithms can be employed to optimize shot peening parameters and improve the quality of the finished product.

In conclusion, the future of shot peening technology is promising, with ongoing research and development leading to improved processes and new applications. These advancements will help to ensure the continued growth and success of shot peening in the years to come.

6. Conclusions

This review provides a comprehensive overview of the current state of the art in shot peening and its associated technologies. It first discusses development and classification of the shot peening technology, including laser shock peening, micro-particle shot peening, high-pressure water jet shot peening and ultrasonic shot peening, and it is found that the traditional shot peening technology is relatively mature and is extensively used nowadays. Then, it provides an overview of numerical investigation of the shot peening process, and it is a powerful method to explore the single particle and random particles shot peening process. Additionally, it highlights the fundamental of the traditional shot peening technology, including the shot peening strengthening process, the shot peening strengthening mechanisms and the shot peening coverage. Finally, this review provides a perspective on the future of shot peening, including the potential for further optimization of peening processes, the development of new peening technologies, and the integration of peening into more comprehensive surface engineering strategies. It also discusses the challenges facing the field of shot peening and suggests directions for future research. Overall, this review provides a comprehensive overview of the current state of the art and future perspectives on surface strengthening by shot peening, and it highlights its potential as a key technology for improving the mechanical properties of materials.

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References

1. Ji, R.; Qi, Z.; Chen, J.; Zhang, L.; Lin, K.; Lu, S.; Li, Y. Numerical and Experimental Investigation on the Abrasive Flow Machining of Artificial Knee Joint Surface. *Crystals* **2023**, *13*, 430. [CrossRef]
2. Yuan, H.; Yang, W.; Zhang, L.; Hong, T. Model Development of Stress Intensity Factor on 7057T6 Aluminum Alloy Using Extended Finite Element Method. *Coatings* **2023**, *13*, 581. [CrossRef]
3. Wang, Y.Y.; Wang, Z.; Ni, P.C.; Wang, D.J.; Guo, S.H.; Chen, Z.Z. Experimental and numerical study on regulation of cutting temperature during the circular sawing of 45 steel. *Coatings* **2023**. *submitted*.
4. Tangwarodomnukun, V.; Kringram, S.; Zhu, H.; Qi, H.; Rujisamphan, N. Fabrication of superhydrophobic surface on AISI316L stainless steel using a nanosecond pulse laser. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2022**, *236*, 680–693. [CrossRef]
5. Saetang, V.; Qi, H.; Smerchit, T.; Rujisamphan, N. Laser scribing of fluorine-doped tin oxide coated on glass substrate in air and water. *Opt. Laser Technol.* **2022**, *153*, 108280. [CrossRef]
6. Qi, H.; Wang, Y.; Qi, Z.; Shi, L.; Fang, Z.; Zhang, L.; Riemer, O.; Karpuschewski, B. A Novel Grain-Based DEM Model for Evaluating Surface Integrity in Scratching of RB-SiC Ceramics. *Materials* **2022**, *15*, 8486. [CrossRef]
7. Charee, W.; Qi, H.; Saetang, V. Underwater laser micromachining of silicon in pressurized environment. *Int. J. Adv. Manuf. Technol.* **2022**, *122*, 3161–3169. [CrossRef]
8. Lei, Y.; Wang, Z.; Qi, H. Strengthening Performance Optimization of Single Ball Impact Treatment by Evaluating Residual Stress. *Materials* **2022**, *15*, 3719. [CrossRef]
9. Qi, H.; Shi, L.; Teng, Q.; Hong, T.; Tangwarodomnukun, V.; Liu, G.; Li, H.N. Subsurface damage evaluation in the single abrasive scratching of BK7 glass by considering coupling effect of strain rate and temperature. *Ceram. Int.* **2022**, *48*, 8661–8670. [CrossRef]
10. Shi, H.; Liu, G.; Yang, G.; Bi, Q.; Zhao, Y.; Wang, B.; Sun, X.; Liu, X.; Qi, H.; Xu, W.; et al. Analytical modelling of edge chipping in scratch of soda-lime glass considering strain-rate hardening effect. *Ceram. Int.* **2021**, *47*, 26552–26566. [CrossRef]
11. Yu, J.; Chen, J.; Ho, H. Effect of laser cladding Ti/B4C/dr40-based composite coatings for the surface strengthening of shaft part. *Opt. Laser Technol.* **2023**, *157*, 108721. [CrossRef]
12. Li, K.; Liu, X.; Liu, Y.; Wu, X.; Zhang, W.; Yang, J.; Li, W.; Zhou, S. Strengthening layer with nano-twins in titanium alloy induced by laser surface re-melting: Mechanism of high strength and ductility. *Mater. Charact.* **2023**, *196*, 112632. [CrossRef]
13. Qian, H.; Chen, M.; Qi, Z.; Teng, Q.; Qi, H.; Zhang, L.; Shan, X. Review on Research and Development of Abrasive Scratching of Hard Brittle Materials and Its Underlying Mechanisms. *Crystals* **2023**, *13*, 428. [CrossRef]
14. Wu, B.; Li, D.R.; Zhou, Y.; Zhu, D.; Zhao, Y.P.; Qiao, Z.K.; Chen, B.; Wang, X.L.; Lin, Q. Construction of a calibration field of absolute gravity in a cave using the Cold Atom Gravimeter. *Sensors* **2023**. *submitted*.
15. Qi, H.; Xing, W.; Tan, W.; Lin, H.; Guo, H.J.; Chen, M.Z.; Tang, H.P. Effect of the sintering process on mechanical behaviors of Zirconia ceramics by NanoParticle Jetting. *Ceram. Int.* **2023**. *submitted*.
16. Xu, Q.; Zhou, J.; Jiang, D.; Yang, X.; Qiu, Z. Improved low-temperature mechanical properties of FH36 marine steel after ultrasonic surface rolling process. *J. Alloys Compd.* **2023**, *937*, 168401. [CrossRef]

17. Yuan, H.; You, Z.; Zhuo, Y.; Ye, X.; Zhu, L.; Yang, W. Numerical and Experimental Study on Reasonable Coverage of Shot Peening on ZGMn13 High Manganese Steel. *Front. Mater.* **2022**, *9*. [CrossRef]
18. Hua, J.; Liu, J.; Liu, P.; Zhao, X.; Chen, C.; Ren, R. Investigation on WEA fatigue spalling of U71MnG rail material subject to laser quenching surface treatment. *Wear* **2023**, *512*, 204560. [CrossRef]
19. Goulmy, J.P.; Boyer, V.; Retraint, D.; Kanoute, P.; Toualbi, L.; Rouhaud, E. Modeling of the shot peening of a nickel alloy with the consideration of both residual stresses and work hardening. *Int. J. Solids Struct.* **2023**, *264*, 112120. [CrossRef]
20. Wang, C.; Lai, Y.; Wang, L.; Wang, C. Dislocation-based study on the influences of shot peening on fatigue resistance. *Surf. Coat. Technol.* **2020**, *383*, 125247. [CrossRef]
21. Wang, Y.; Huang, A.; Wu, M.; Gu, H. Corrosion of alumina-magnesia castable by high manganese steel with respect to steel cleanness. *Ceram. Int.* **2019**, *45*, 9884–9890. [CrossRef]
22. Chen, H.; Wang, S.; Lu, S.; Qiao, Y.; Wang, X.; Fan, N.; Guo, P.; Niu, J. Simulation and experimental validation of residual stress and surface roughness of high manganese steel after shot peening. *Procedia CIRP* **2018**, *71*, 227–231. [CrossRef]
23. Bagheri, S.; Guagliano, M. Review of shot peening processes to obtain nanocrystalline surfaces in metal alloys. *Surf. Eng.* **2009**, *25*, 3–14. [CrossRef]
24. Bagherifard, S. Enhancing the Structural Performance of Lightweight Metals by Shot Peening. *Adv. Eng. Mater.* **2019**, *21*, 1801140. [CrossRef]
25. Świetlicki, A.; Szala, M.; Walczak, M. Effects of Shot Peening and Cavitation Peening on Properties of Surface Layer of Metallic Materials—A Short Review. *Materials* **2022**, *15*, 2476. [CrossRef]
26. Soyama, H.; Korsunsky, A.M. A critical comparative review of cavitation peening and other surface peening methods. *J. Mater. Process. Technol.* **2022**, *305*, 117586. [CrossRef]
27. Menezes, M.R.; Godoy, C.; Buono, V.T.L.; Schvartzman, M.M.M.; Avelar-Batista Wilson, J.C. Effect of shot peening and treatment temperature on wear and corrosion resistance of sequentially plasma treated AISI 316L steel. *Surf. Coat. Technol.* **2017**, *309*, 651–662. [CrossRef]
28. González, J.; Bagherifard, S.; Guagliano, M.; Fernández Pariente, I. Influence of different shot peening treatments on surface state and fatigue behaviour of Al 6063 alloy. *Eng. Fract. Mech.* **2017**, *185*, 72–81. [CrossRef]
29. Gerin, B.; Pessard, E.; Morel, F.; Verdu, C. Influence of surface integrity on the fatigue behaviour of a hot-forged and shot-peened C70 steel component. *Mater. Sci. Eng. A* **2017**, *686*, 121–133. [CrossRef]
30. 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]
31. Rubio-González, C.; Ocaña, J.L.; Gomez-Rosas, G.; Molpeceres, C.; Paredes, M.; Banderas, A.; Porro, J.; Morales, M. Effect of laser shock processing on fatigue crack growth and fracture toughness of 6061-T6 aluminum alloy. *Mater. Sci. Eng. A* **2004**, *386*, 291–295. [CrossRef]
32. Zhang, H.; Cai, Z.; Chi, J.; Sun, R.; Che, Z.; Zhang, H.; Guo, W. Fatigue crack growth in residual stress fields of laser shock peened Ti6Al4V titanium alloy. *J. Alloys Compd.* **2021**, *887*, 161427. [CrossRef]
33. Chung, Y.-H.; Chen, T.-C.; Lee, H.-B.; Tsay, L.-W. Effect of Micro-Shot Peening on the Fatigue Performance of AISI 304 Stainless Steel. *Metals* **2021**, *11*, 1408. [CrossRef]
34. 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]
35. Morita, T.; Noda, S.; Kagaya, C. Influences of Fine-Particle Bombarding and Conventional Shot Peening on Surface Properties of Steel. *Mater. Trans.* **2014**, *55*, 646–652. [CrossRef]
36. Chakkravarthy, V.; Oliveira, J.P.; Mahomed, A.; Yu, N.; Manojkumar, P.; Lakshmanan, M.; Zhang, L.; Raja, V.; Jerome, S.; Prabhu, T.R.; et al. Effect of abrasive water jet peening on NaCl-induced hot corrosion behavior of Ti–6Al–4V. *Vacuum* **2023**, *210*, 111872. [CrossRef]
37. Soyama, H. Comparison between the improvements made to the fatigue strength of stainless steel by cavitation peening, water jet peening, shot peening and laser peening. *J. Mater. Process. Technol.* **2019**, *269*, 65–78. [CrossRef]
38. Kumar, P.; Mahobia, G.S.; Singh, V.; Chattopadhyay, K. Low cycle fatigue behaviour of Ti-13Nb-13Zr alloy in ultrasonic shot peened and stress relieved condition. *Int. J. Fatigue* **2023**, *166*, 107289. [CrossRef]
39. Tao, N.R.; Wang, Z.B.; Tong, W.P.; Sui, M.L.; Lu, J.; Lu, K. An investigation of surface nanocrystallization mechanism in Fe induced by surface mechanical attrition treatment. *Acta Mater.* **2002**, *50*, 4603–4616. [CrossRef]
40. Badreddine, J.; Rouhaud, E.; Micoulaut, M.; Retraint, D.; Remy, S.; François, M.; Viot, P.; Doubre-Baboeuf, G.; Saunier, D.B.L.; Desfontaine, V. Simulation and experimental approach for shot velocity evaluation in ultrasonic shot peening. *Mech. Ind.* **2011**, *12*, 223–229. [CrossRef]
41. Okura, Y.; Sasaki, H.; Soyama, H. Effect of Mechanical Properties on Fatigue Life Enhancement of Additive Manufactured Titanium Alloy Treated by Various Peening Methods. In Proceedings of the Advanced Surface Enhancement, Singapore, 10–13 September 2020; pp. 88–96.
42. Kokubun, T.; Soyama, H. Evaluation of fatigue crack propagation in surface modification layer of duralumin treated by various peening. *Trans. JSME* **2017**, *83*, 1–15.
43. Bai, F.; Saalbach, K.-A.; Wang, L.; Wang, X.; Twiefel, J. Impact of time on ultrasonic cavitation peening via detection of surface plastic deformation. *Ultrasonics* **2018**, *84*, 350–355. [CrossRef] [PubMed]

44. Gao, Y.; Wu, B.; Liu, Z.; Zhou, Y.; Shen, N.; Ding, H. Ultrasonic Cavitation Peening of Stainless Steel and Nickel Alloy. *J. Manuf. Sci. Eng.* **2013**, *136*, 014502. [CrossRef]
45. Mathias, M.; Göcke, A.; Pohl, M. The residual stress, texture and surface changes in steel induced by cavitation. *Wear* **1991**, *150*, 11–20. [CrossRef]
46. Cheng, Z.; Qin, S.; Fang, Z. Numerical Modeling and Experimental Study on the Material Removal Process Using Ultrasonic Vibration-Assisted Abrasive Water Jet. *Front. Mater.* **2022**, *9*, 250. [CrossRef]
47. Qi, H.; Wen, D.; Lu, C.; Li, G. Numerical and experimental study on ultrasonic vibration-assisted micro-channelling of glasses using an abrasive slurry jet. *Int. J. Mech. Sci.* **2016**, *110*, 94–107. [CrossRef]
48. Qi, H.; Wen, D.; Yuan, Q.; Zhang, L.; Chen, Z. Numerical investigation on particle impact erosion in ultrasonic-assisted abrasive slurry jet micro-machining of glasses. *Powder Technol.* **2017**, *314*, 627–634. [CrossRef]
49. Zhang, L.; Yuan, Z.; Qi, Z.; Cai, D.; Cheng, Z.; Qi, H. CFD-based study of the abrasive flow characteristics within constrained flow passage in polishing of complex titanium alloy surfaces. *Powder Technol.* **2018**, *333*, 209–218. [CrossRef]
50. Zhang, L.; Ji, R.; Fu, Y.; Qi, H.; Kong, F.; Li, H.; Tangwarodomnukun, V. Investigation on particle motions and resultant impact erosion on quartz crystals by the micro-particle laden waterjet and airjet. *Powder Technol.* **2020**, *360*, 452–461. [CrossRef]
51. Qi, H.; Qin, S.; Cheng, Z.; Zou, Y.; Cai, D.; Wen, D. DEM and experimental study on the ultrasonic vibration-assisted abrasive finishing of WC-8Co cemented carbide cutting edge. *Powder Technol.* **2021**, *378*, 716–723. [CrossRef]
52. Hu, W.; Teng, Q.; Hong, T.; Saetang, V.; Qi, H. Stress field modeling of single-abrasive scratching of BK7 glass for surface integrity evaluation. *Ceram. Int.* **2022**, *48*, 12819–12828. [CrossRef]
53. Qi, H.; Qin, S.; Cheng, Z.; Teng, Q.; Hong, T.; Xie, Y. Towards understanding performance enhancing mechanism of micro-holes on K9 glasses using ultrasonic vibration-assisted abrasive slurry jet. *J. Manuf. Process.* **2021**, *64*, 585–593. [CrossRef]
54. Zhou, J.; Sun, Z. Numerical characterization of shot peening induced work hardening gradient and verification based on FEM analysis. *Int. J. Solids Struct.* **2022**, *244*, 111586. [CrossRef]
55. Marini, M.; Piona, F.; Fontanari, V.; Bandini, M.; Benedetti, M. A new challenge in the DEM/FEM simulation of the shot peening process: The residual stress field at a sharp edge. *Int. J. Mech. Sci.* **2020**, *169*, 105327. [CrossRef]
56. Murugaratnam, K.; Utili, S.; Petrinic, N. A combined DEM–FEM numerical method for Shot Peening parameter optimisation. *Adv. Eng. Softw.* **2015**, *79*, 13–26. [CrossRef]
57. Zhao, J.; Tang, J.; Zhou, W.; Jiang, T.; Liu, H.; Xing, B. Numerical modeling and experimental verification of residual stress distribution evolution of 12Cr2Ni4A steel generated by shot peening. *Surf. Coat. Technol.* **2022**, *430*, 127993. [CrossRef]
58. Meguid, S.A.; Shagal, G.; Stranart, J.C.; Daly, J. Three-dimensional dynamic finite element analysis of shot-peening induced residual stresses. *Finite Elem. Anal. Des.* **1999**, *31*, 179–191. [CrossRef]
59. Kim, T.; Lee, H.; Hyun, H.C.; Jung, S. Effects of Rayleigh damping, friction and rate-dependency on 3D residual stress simulation of angled shot peening. *Mater. Des.* **2013**, *46*, 26–37. [CrossRef]
60. Hong, T.; Wang, Z.W.; Yuan, J.L. Numerical simulation of shot peening process using Finite Element and Discrete Element Method. *China Mech. Eng.* **2008**, *19*, 0–1316.
61. Liu, C.C. *Finite Element Simulation of Shot Peening and its Experimental Verfication*; Northeastern University: Boston, MA, USA, 2014.
62. Wang, L.P. *Numerical Simulation Research for Compressive Residual Stress and Surface Roughness of Shot Peening*; Shandong University: Jinan, China, 2015.
63. Majzoobi, G.H.; Azizi, R.; Alavi Nia, A. A three-dimensional simulation of shot peening process using multiple shot impacts. *J. Mater. Process. Technol.* **2005**, *164*, 1226–1234. [CrossRef]
64. Li, Y.Z.; Wang, F.; Lv, J.; Xu, K.W. Finite Element analysis for shot-peening models of single shot impact and multiple impingment. *J. Xi'an Jiaotong Univ.* **2007**, *41*, 5.
65. Zhang, H.W.; Chen, J.Q.; Zhang, Y.D. Numerical simulation of shot-peening process based on multiple shot model. *J. Plast. Eng.* **2012**, *19*, 8.
66. Miao, H.Y.; Larose, S.; Perron, C.; Levesque, M. On the potential applications of a 3D random finite element model for the simulation of shot peening. *Adv. Eng. Softw.* **2009**, *40*, 1023–1038. [CrossRef]
67. Li, Y.; Lei, L.P.; Zeng, P. Shot stream Finite Element model for shot peening numerical simulation and its experimental study. *J. Mech. Eng.* **2011**, *47*, 6. [CrossRef]
68. Wang, Y.Z.; Li, F.; Chen, Y.Y.; Zhang, Y.P.; Wu, Z.G.; Wang, C. TC4 shot peening simulation and experiment. *J. Beijing Univ. Aeronaut. Astronaut.* **2019**, *9*, 1723–1731.
69. Sheng, X.F.; Li, Z.; Zhao, K.Y.; Cheng, X.Q. Numerical simulation research on strengthening effect of shot peening at identical intensity. *Surf. Technol.* **2018**, *47*, 7.
70. Qin, Z.; Li, B.; Zhang, H.; Youani Andre Wilfried, T.; Gao, T.; Xue, H. Effects of shot peening with different coverage on surface integrity and fatigue crack growth properties of 7B50-T7751 aluminum alloy. *Eng. Fail. Anal.* **2022**, *133*, 106010. [CrossRef]
71. Unal, O.; Varol, R. Almen intensity effect on microstructure and mechanical properties of low carbon steel subjected to severe shot peening. *Appl. Surf. Sci.* **2014**, *290*, 40–47. [CrossRef]
72. Guagliano, M. Relating Almen intensity to residual stresses induced by shot peening: A numerical approach. *J. Mater. Process. Technol.* **2001**, *110*, 277–286. [CrossRef]
73. Xin, Z.L. Shot peening process design intensit. *Tool Eng.* **2018**, *52*, 4.

74. Su, K.; Zhang, J.; Li, H.; Ji, D.; Hu, L. Anti-fatigue strengthening mechanism of conventional shot peening and micro-shot peening on bare and micro-arc oxidation coated 6082-T6 aluminum alloy. *Mater. Lett.* **2023**, *331*, 133442. [CrossRef]
75. Fang, B.W. *Controlled Shot Peening and Residual Stress Theory*; Shandong Science and Technology Press: Jinan, China, 1991.
76. Choi, Y. Influence of rake angle on surface integrity and fatigue performance of machined surfaces. *Int. J. Fatigue* **2017**, *94*, 81–88. [CrossRef]
77. Gao, Y.K. Improvement of fatigue property in 7050–T7451 aluminum alloy by laser peening and shot peening. *Mater. Sci. Eng. A* **2011**, *528*, 3823–3828. [CrossRef]
78. Wang, Z.; Xie, L.; Zhang, Q.; Ali, R.A.; Chen, W.; Zhou, L. Surface layer strengthening mechanism of 2060 aluminum–lithium alloy after shot-peening. *J. Mater. Res. Technol.* **2023**, *23*, 4615–4633. [CrossRef]
79. Li, W.; Liu, P.; Zhao, S.; Zhang, K.; Ma, F.; Liu, X.; Chen, X.; He, D. Microstructural evolution, mechanical properties and strengthening mechanism of TiN/Ni nanocomposite film. *J. Alloys Compd.* **2017**, *691*, 159–164. [CrossRef]
80. Yin, F.; Zhang, X.; Chen, F.; Hu, S.; Ming, K.; Zhao, J.; Xie, L.; Liu, Y.; Hua, L.; Wang, J. Understanding the microstructure refinement and mechanical strengthening of dual-phase high entropy alloy during ultrasonic shot peening. *Mater. Des.* **2023**, *227*, 111771. [CrossRef]
81. Gangaraj, S.M.H.; Guagliano, M.; Farrahi, G.H. An approach to relate shot peening finite element simulation to the actual coverage. *Surf. Coat. Technol.* **2014**, *243*, 39–45. [CrossRef]
82. Li, R.; Liu, D.; Wei, Z.; Xuan, L.; Qiao, M.; Xia, M. Influence of shot peening and surface integrity on the fatigue properties of 300M steel. *Mech. Sci. Technol. Aerosp. Eng.* **2011**, *30*, 1418–1423.
83. Wu, J.; Liu, H.; Wei, P.; Zhu, C.; Lin, Q. Effect of shot peening coverage on hardness, residual stress and surface morphology of carburized rollers. *Surf. Coat. Technol.* **2020**, *384*, 125273. [CrossRef]
84. Zhang, L. *Analysis and Research of Shot Peening Coverage*; Soochow University: Suzhou, China, 2015.