

Review

Research Progress on Post-Treatment Technologies of Cold Spray Coatings

Yueyu Huang¹, Haifeng Li², Jianwu Liu², Zizhao Wu², Qun Wang^{1,*} and Chidambaram Seshadri Ramachandran³

¹ College of Materials Science and Engineering, Hunan University, Changsha 410082, China; 17758586244@163.com

² AECC Hunan Aviation Powerplant Research Institute, Zhuzhou 412002, China; lihaifeng3737@163.com (H.L.); jianwuliu8678@163.com (J.L.); as02071731@163.com (Z.W.)

³ Department of Materials Science and Engineering, The State University of New York (SUNY) Stony Brook, New York, NY 11794, USA; csrcl1@gmail.com

* Correspondence: wangqun@hun.edu.cn

Abstract: Cold spraying (CS), also known as cold gas dynamic spraying or supersonic cold spraying, is a process in which particles collide with the substrate at a speed greater than the critical value and deposit layer by layer to form a coating. As an emerging coating preparation technology that has been developed rapidly in recent years, CS is characterized by a low deposition temperature, a minimal thermal effect on substrate, and a high deposition efficiency. It has received extensive attention from industry. However, the inherent high strength and low plasticity of CS coatings and the numerous defects present limit their wider application to some extent. Therefore, various post-treatment technologies are successfully applied to the CS coatings to improve their comprehensive performance. This paper reviews the latest research progress of common post-treatment techniques for CS coatings, including five categories: thermal, mechanical, thermo-mechanical, chemical, and electrochemical processing. A considerable amount of experimental research has demonstrated that post-treatment can effectively enhance the microstructure and properties of CS coatings, and this can serve as a powerful approach to expand the application scope of CS technology. In addition, the relevant post-processing parameters and corresponding results are summarized and compared systematically.



Academic Editor: Uta Klement

Received: 26 January 2025

Revised: 13 February 2025

Accepted: 20 February 2025

Published: 23 February 2025

Citation: Huang, Y.; Li, H.; Liu, J.; Wu, Z.; Wang, Q.; Ramachandran, C.S. Research Progress on Post-Treatment Technologies of Cold Spray Coatings. *Coatings* **2025**, *15*, 265. <https://doi.org/10.3390/coatings15030265>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: cold spraying; high strength and low plasticity; post-treatment; post-processing parameters; microstructure; properties

1. Introduction

Cold spraying (CS), also referred to as cold gas dynamic spraying (CGDS), was discovered by Soviet scientist Anatolii Papyrin and his team in the mid-1980s, and the concept was put forward in 1990 [1]. As a novel solid-state deposition technology, cold spraying is characterized by low thermal input to the substrate, wide material applicability, dense coatings, high deposition efficiency, and fast speed. It can be employed for the preparation of high-quality coatings, additive manufacturing [2], and the joining [3] and repair [2] of metal components, having garnered extensive attention and application in domains such as aerospace, mechanical equipment, energy, and power, possessing tremendous development potential.

The typical composition and fundamental principle of a CS system are depicted in Figure 1. In the CS process, high-pressure gases (such as N₂, He, and air) pass through specially designed convergent-divergent Laval nozzles to obtain supersonic gas flows.

These gas flows accelerate powder particles (typically ranging from 5 to 100 μm) to velocities above the critical value (300–1400 m/s) and then impact the substrate, achieving bonding with the substrate and among themselves through the formation of adiabatic shear bands [1,4,5]. Compared with thermal spraying, the temperature of powder particles remains below the melting point in the CS process since the deposits have almost no thermally induced defects, such as oxidation, phase transformation, grain coarsening, and thermally induced residual stress [2,5], making it particularly suitable for temperature-sensitive materials (such as nanocrystalline [6] and amorphous [7] materials) and materials prone to oxidation (such as Mg [8], Al [9], Ti [10], etc.). However, in actual engineering applications, several major shortcomings of CS have also been discovered [5,11–13]: (1) The presence of numerous defects and weakly bonded particle interfaces hinders the attainment of bulk material-level performance in CS coatings regarding mechanical, tribological, and corrosion-resistant properties. (2) Within CS composite coatings, ceramic–metal particle interactions remain predominantly limited to physical contact, significantly constraining wear resistance enhancement. (3) Direct establishment of complete metallurgical bonds between CS coatings and substrates proves challenging, with residual stress accumulation further compromising interfacial adhesion strength. These deficiencies severely restrict the application of CS. Although adjusting various process parameters of CS (such as nozzle, powder, and gas) can improve the coating quality, the effect is limited. Therefore, post-treatment is essential to effectively enhance the performance of CS coatings to meet industrial usage requirements and broaden their application fields. Several common post-treatment methods for CS coatings are shown in Figure 2.

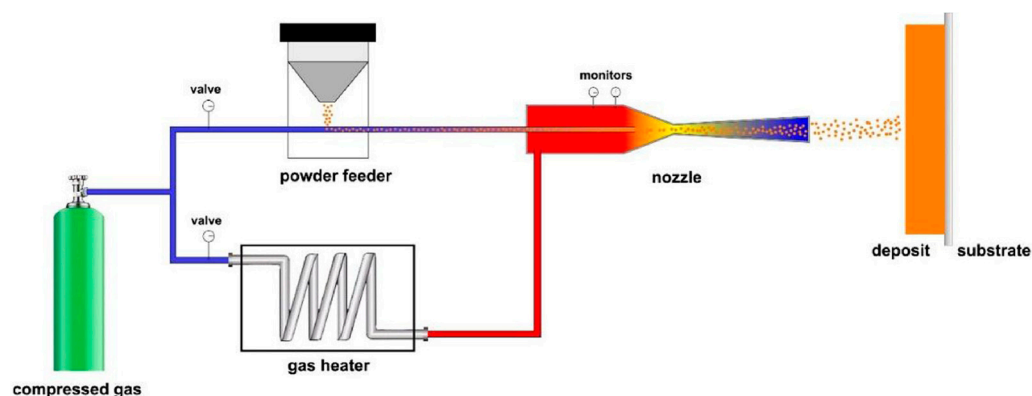


Figure 1. Schematic diagram of the working principle of cold spraying (adapted from reference [2], © Elsevier).

There is still a lack of comprehensive reviews on post-treatment technologies for cold spray coatings. To better understand the post-treatment technologies and their current development status, this paper will comprehensively and critically review various common post-treatment methods for CS coatings, including heat treatment (HT), laser remelting (LR), friction stir processing (FSP), shot peening (SP), hot rolling (HR), chemical conversion coating (CCC), anodic oxidation (AO), and plasma electrolytic oxidation (PEO). The relevant research and key process parameters are also summarized. Finally, the research progress and deficiencies in the post-treatment of CS coatings at the present stage are outlined, and future research work is also prospected, aiming to provide references for the continuous advancement and engineering application of post-treatment technologies for CS coatings.

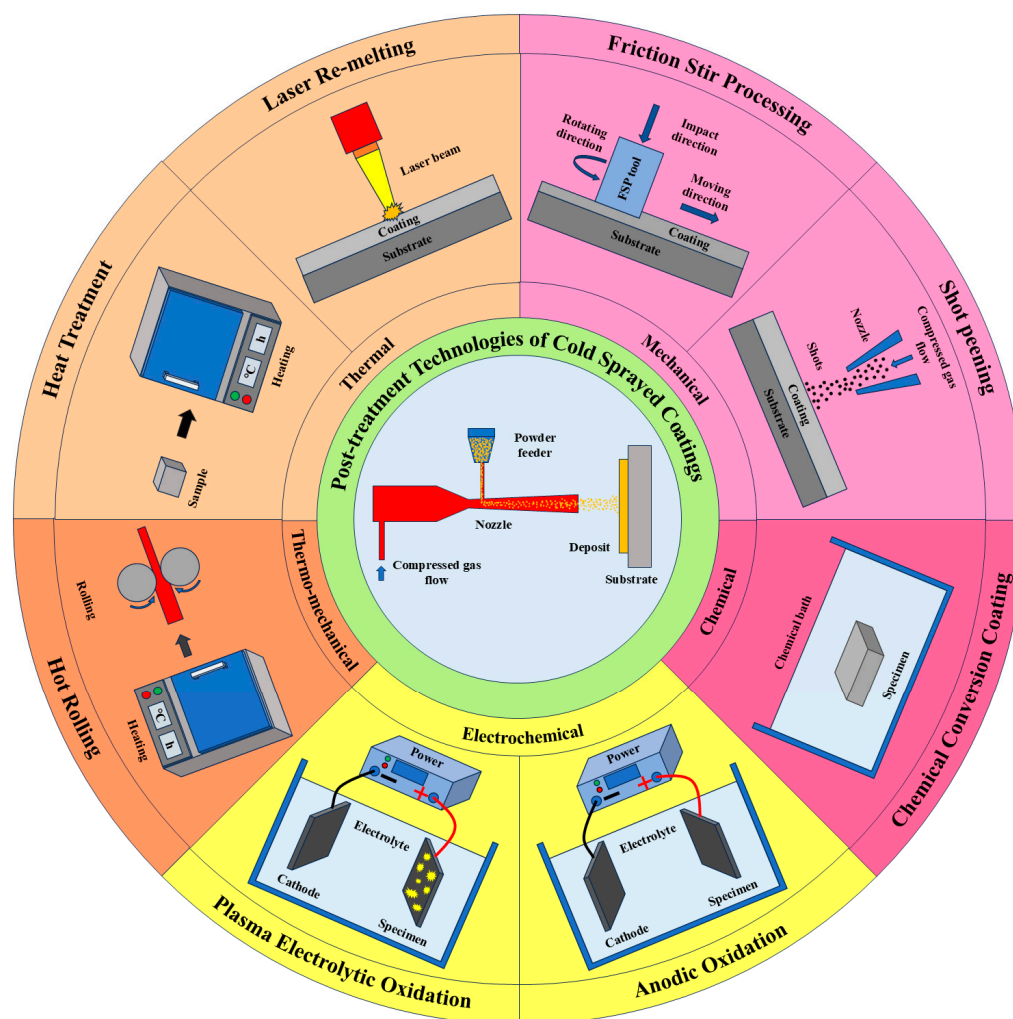


Figure 2. Eight post-treatment technologies of cold sprayed coatings.

2. Thermal Processing

2.1. Heat Treatment

Heat treatment (HT) is currently the most extensively utilized post-treatment process for CS coatings. Heat heating facilitates atomic diffusion within the coating to eliminate defects such as pores and cracks, thereby achieving coating modification. HT can usually be implemented through traditional furnaces or electromagnetic induction heating [14,15], and the heating temperature is maintained beneath the melting point of materials. Table 1 summarizes the research in this aspect.

Table 1. Effect of heat treatment on CS coatings.

References	Coatings	HT Parameters	Findings
[16]	Ag	Temperature: 400–800 °C Span: 3 h, 10 h Environment: Air, Ar	After HT, the coating's hardness and porosity were reduced while the grain size increased. The highest conductivity was observed in an Ar atmosphere at 400 °C.
[17]	Cu	Temperature: 300 °C Span: 1 h Environment: Vacuum	After HT, the coating's conductivity approaches that of annealed copper, and the hardness is significantly reduced. The porosity can be minimized in a vacuum environment.

Table 1. Cont.

References	Coatings	HT Parameters	Findings
[18]	Cu	Temperature: 300–700 °C Span: 3 h Environment: Air	HT can mitigate the pronounced anisotropy of tensile strength in the coating layer; however, its influence on the anisotropy of elongation remains relatively limited. When the HT temperature reaches 350 °C, the coating's microhardness attains its peak value. As the temperature increases, the coating's microhardness diminishes, primarily due to the coarsening of Cr ₂ Nb and the softening of the Cu matrix.
[19]	Cu-4Cr-2Nb	Temperature: 250–950 °C Span: 2 h Environment: Vacuum	HT can enhance the density of the coating structure, increase the bonding strength between the coating and the substrate, and improve its corrosion resistance compared to aluminum blocks.
[14]	Al	Temperature: 300 °C Span: 1 h Environment: Vacuum	HT forms an intermetallic compound layer between the coating and the AZ91 substrate, thereby achieving a favorable metallurgical bonding.
[20]	Al	Temperature: 400 °C Span: 20 h Environment: Ar	After HT at 600 °C, the coating's elongation reaches approximately 50% of that of the bulk material, while its tensile strength remains comparable to that of the bulk material. However, the yield strength is significantly diminished.
[21]	Al	Temperature: 200–600 °C Span: 4 h Environment: Ar	HT initiated the recovery and recrystallization of the coating structure, thereby reducing porosity and microhardness while partially restoring plasticity.
[22]	7075Al	Temperature: 200–400 °C Span: 3 h Environment: Air	Following HT, the coating's tensile strength and ductility are enhanced. This improvement can be attributed to metallurgical bonding at the particle interfaces and a moderate increase in the density of reinforcing precipitates.
[23]	6061Al	Temperature: 176 °C Span: 1 h, 8 h Environment: Air	After HT, the enhancement in coating strength can primarily be attributed to an increased metallurgical bonding ratio between particles. However, reduced hardness diminishes wear resistance.
[24]	2024Al	Temperature: 300–500 °C Span: 4 h Environment: Air	HT is an effective method to significantly reduce the porosity of the coating, with this effect becoming increasingly pronounced as the temperature increases.
[25]	C355Al	Temperature: 175–250 °C Span: 4 h Environment: Air	HT enhances the adhesion between the coating and the substrate through promoting atomic diffusion.
[26]	5356Al// 5356Al/TiN	Temperature: 250–450 °C Span: 2 h Environment: Vacuum	However, it has negligible influence on TiN particle size, morphology and distribution, and the coatings' hardness is reduced due to the release of deformation stress.
[27]	Al-25Ni// Al-25Ti	Temperature: 450–630 °C Span: 4 h Environment: N ₂	After HT, the two types of coatings developed uniform intermetallic compounds, significantly enhancing their microhardness.
[28]	Zn	Temperature: 150 °C Span: 1 h Environment: Vacuum	After HT, the coating's porosity decreased from 0.47% to 0.25%, slightly reducing hardness, while the corrosion resistance was markedly enhanced.
[29]	Ti	Temperature: 850 °C Span: 4 h Environment: Ar	Micro-CT analysis revealed that the coating's overall porosity slightly decreased following HT, with the pores undergoing shrinkage and spheroidization.
[30]	WC/Ti	Temperature: 550 °C Span: 1 h Environment: Ar	HT can significantly increase the composite coating's hardness. However, it fails to effectively enhance the wear resistance, which is attributed to the transfer of the abrasive material.
[31]	Ti-6Al-4V	Temperature: 575–1050 °C Span: 2 h Environment: Vacuum	HT can achieve high strength and high ductility in the temperature range of 950 °C to 1050 °C, with the coating's tensile properties comparable to those of forged materials.

Table 1. Cont.

References	Coatings	HT Parameters	Findings
[32]	Nb	Temperature: 500–1500 °C Span: 2 h Environment: Vacuum	After HT at or above 1250 °C, most pores and interparticle interfaces within the coating are eliminated. Consequently, the coating's elastic modulus, tensile strength, and corrosion resistance approach those of Nb bulk material.
[33]	Ni	Temperature: 600 °C Span: 2 h Environment: Ar-3% H_2	HT densified the coating, enhancing its corrosion resistance. However, recrystallization reduced the hardness.
[34]	IN625	Temperature: 900 °C Span: 10 min Environment: Ar	Compared to conventional HT furnaces, induction heating enables the coating to achieve superior bonding strength and enhanced plasticity in a shorter period due to the presence of eddy currents.
[35]	IN718	Temperature: 990 °C Span: 4 h Environment: Ar	After HT, the coating's tensile strength, elongation, and Young's modulus exhibit substantial improvements. Notably, the coating's tensile strength approaches that of the bulk material.
[36]	IN718	Temperature: 950–1250 °C Span: 1 h, 2 h Environment: Ar-10% H_2	After HT, the coating's elongation reaches 24.7%, and its tensile strength is approximately 62% that of the bulk material.
[37]	Fe-40Al	Temperature: 650–1100 °C Span: 5 h Environment: Ar	After HT, Fe-Al intermetallic compounds are formed within the coating, and the interparticle bonding is significantly enhanced, thereby substantially improving the coating's corrosion resistance.
[38]	SS304	Temperature: 300–950 °C Span: 1 h Environment: Vacuum	After HT, the coating transforms from an anisotropic structure to a uniform equiaxed structure, resulting in a significant increase in tensile strength and a noticeable decrease in hardness.
[39]	SS316L	Temperature: 400–1100 °C Span: 1 h Environment: Air	HT decreases the coating's porosity, enhances interlayer bonding, and improves the elastic modulus and corrosion resistance.
[40]	CoNiCrAlY	Temperature: 1050 °C Span: 4 h Environment: Vacuum	Following the pre-oxidation HT, a dense oxide layer forms on the surface, which can substantially enhance the coating's oxidation resistance.
[41]	CoNiCrAlY	Temperature: 800–1100 °C Span: 10 min Environment: Vacuum	Owing to the presence of eddy currents, the areas surrounding the pores are preferentially heated, and a majority of the pores can be eliminated within a short period of time. HT decreases the coating's hardness at higher temperature, which is associated with grain growth and stress release.
[42]	Ni/FeSiAl	Temperature: 200–800 °C Span: 2 h Environment: Ar	After HT, the coating's soft magnetic properties are significantly enhanced due to stress relief and grain growth within the coating.

CS coatings typically exhibit a lamellar structure, which can be categorized into dense-state and porous-state coatings depending on material properties and processing parameters. The HT of CS coatings essentially constitutes a solid-state sintering process involving three primary stages, including recovery, recrystallization, and grain growth, which are driven by diffusion mechanisms that ultimately transform the lamellar structure into a homogeneous microstructure, as illustrated in Figure 3. Taking atmospheric-pressure sintering of single-component CS coatings as an example, during the initial sintering stage (diffusion-dominated phase), surface diffusion serves as the principal mechanism propelled by interfacial energy reduction. Dense-state coatings demonstrate intimate particle contact with nearly eliminated interfaces, while porous-state coatings develop sintering necks between particles. The intermediate sintering stage (recrystallization phase) becomes governed by grain boundary and lattice diffusion, driven by the release of stored internal energy from particle deposition. Both coating types develop numerous fine equiaxed grains during this phase, with most residual stresses being eliminated. In porous coatings,

sintering necks continue growing while most pores transform into closed porosity. The final sintering stage (grain growth phase) features significant grain coarsening dominated by lattice diffusion, with grain boundary energy reduction providing the driving force. Closed pores undergo spheroidization through surface energy minimization and diffusion mechanisms, while pores failing to migrate with grain boundaries become trapped within the coating microstructure. This explains HT's limited efficacy in reducing porosity for porous-state coatings, consistent with practical observations [21,29]. Although elevating HT temperature or extending dwell time could enhance porosity reduction, strict parameter control remains crucial as excessive thermal input may induce secondary recrystallization or thermal cracking, significantly compromising mechanical properties. Furthermore, hot-press sintering promotes pore closure through plastic deformation or creep under external pressure, while vacuum sintering amplifies pressure differentials between pores and ambient environment. Both methods demonstrating superior pore elimination efficiency compared to conventional approaches.

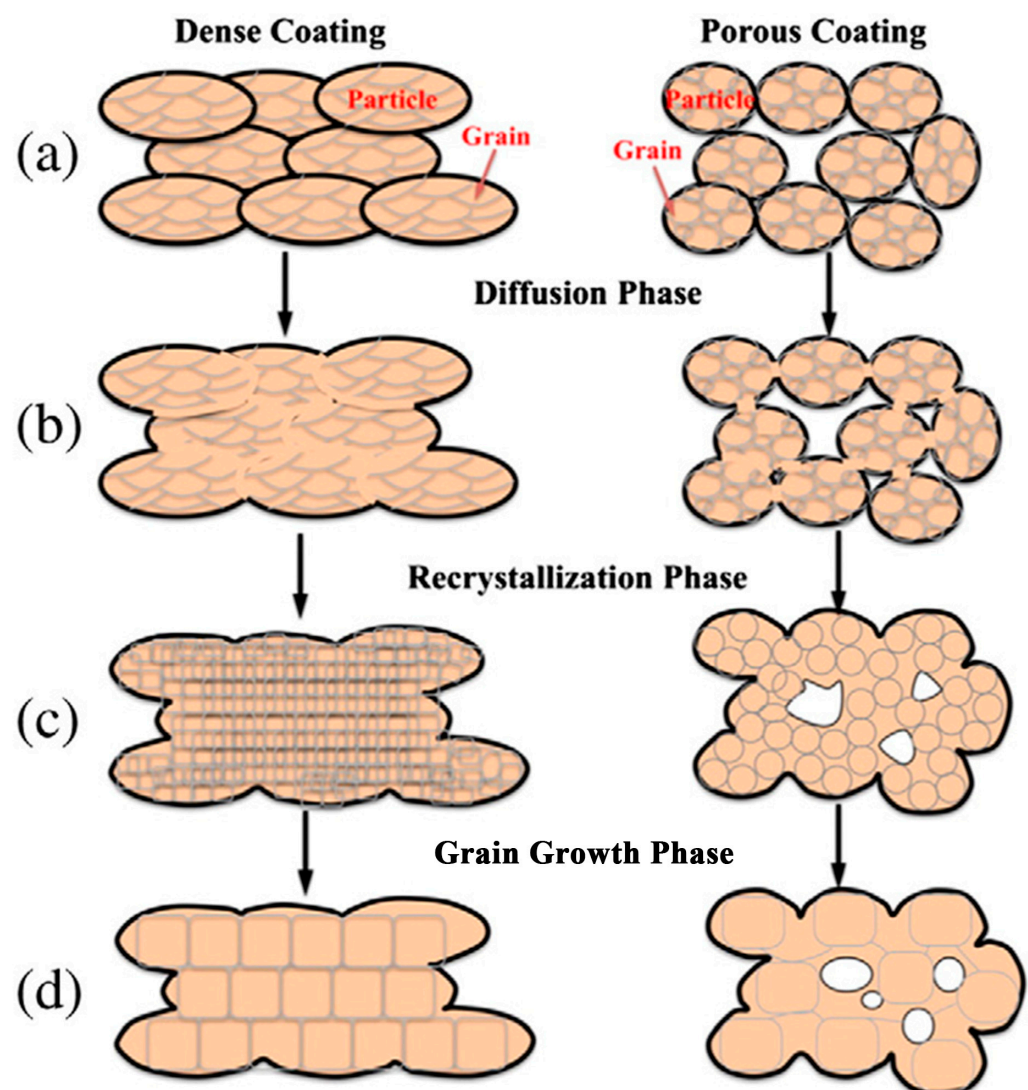


Figure 3. Microstructure evolution of cold sprayed dense and porous deposits during HT (adapted from reference [21], © Elsevier). (a) before HT; (b) after diffusion phase; (c) after recrystallization phase; (d) after grain growth phase.

Sufficient plasticity and strength ensure material integrity during subsequent machining and service applications, however CS coatings inherently exhibit limited ductility due

to plastic deformation exhaustion during deposition and abundant weakly-bonded particle interfaces. HT induces significant recrystallization of deformed grains, transforming anisotropic microstructures into homogeneous equiaxed configurations [38] while eliminating defects and converting mechanical interfaces into metallurgical bonds through healing mechanisms, establishing HT as a straightforward and effective approach for enhancing coating plasticity and tensile strength. Nevertheless, HT typically reduces coating hardness through substantial dislocation density reduction and residual stress relief [35], diminishing deposition-induced work hardening effects and potentially compromising wear resistance. Notably, when interparticle reactions during HT generate high-hardness compounds in composite coatings, significant hardness enhancement can be achieved [27]. Beyond mechanical improvements, microstructural densification, interfacial healing, and dislocation density reduction synergistically enhance corrosion resistance, tribological performance, and electrical conductivity in CS coatings.

Temperature is an extremely critical influencing factor in the HT of CS coatings. Murray et al. [25] studied the influence of HT temperature on the microstructure of CS C335Al coating. The results demonstrated that the coating reduced the porosity through the diffusion mechanism, and the effect was more pronounced with the increase in temperature. At an HT temperature of 250 °C, the density of the coating had reached the level of the bulk material. Kumar et al. [32] discovered that the HT temperature significantly impacted the grain size of Nb coating. At relatively low temperatures, no obvious grain structure emerged in the coating. When the temperature rose above the recrystallization temperature, new grains began to form. As the temperature increased, the grain size became increasingly coarse. Hence, when conducting HT on CS coatings, the temperature should be above the material's recrystallization temperature. An overly low temperature fails to provide sufficient energy for the atoms to diffuse adequately, resulting in the difficulty of eliminating defects such as pores, cracks, and inclusions in coatings since the density cannot be significantly enhanced. Furthermore, an excessively high temperature is prone to causing grain coarsening and composition segregation; it will also generate more inclusions in an atmospheric environment [21,32,43], all of which will severely deteriorate the performance of coatings.

Furthermore, the heating atmosphere significantly influences the microstructure and properties of coatings. Yin et al. [43] discovered that, in comparison with the air atmosphere, vacuum annealing can markedly enhance the tensile strength and plasticity of the SS316L coating. The reason is that no oxide inclusions are formed at the particle interfaces, facilitating the tight bonding between particles. For CS Ag coating [16], HT carried out in an argon atmosphere can yield a higher electrical conductivity than in an air atmosphere. This is primarily determined by the oxide content at the particle interfaces; the fewer the inclusions there are, the higher the electrical conductivity. In reality, when most metal or alloy coating materials undergo HT in air, oxidation is prone to occur, and the generated oxides and other inclusions will severely impede the diffusion of atoms between particles, thereby hindering the recovery and recrystallization processes and making it difficult to eliminate defects. However, these detrimental effects can be effectively avoided by conducting the HT in a vacuum or inert protective gas atmosphere. It is important to note that oxygen in the HT environment is not always harmful. For instance, the oxidation resistance of CoNiCrAlY coating [40] can be significantly enhanced after pre-oxidation heat treatment in air. Therefore, the selection of a suitable heating atmosphere is crucial for different materials.

Research on the HT of CS coatings is mainly carried out using heating furnaces. Yet, furnace heat treatment suffers from low heating efficiency and the propensity of materials to oxidize. In recent years, some researchers have initiated attempts to employ

electromagnetic induction heating for the HT of CS coatings. The eddy currents generated in the coating through induction heating can facilitate atomic diffusion, which is conducive to the progress of recovery and recrystallization processes. Sun et al. [15] were the first to compare the effects of induction heating and traditional furnace heat treatment on CS Inconel 718 coating. The results indicated that within the same 10-minute heating period, induction heating eliminated the majority of pores and cracks in the coating and significantly ameliorated the bonding morphology between the coating and the substrate (Figure 4c). On the other hand, furnace heating barely alters the microstructure of the coating (Figure 4b). Subsequent research by Yang et al. [41] yielded similar results. Due to the higher resistance in the vicinity of pores, more Joule heat is generated in this region by the eddy currents (Figure 4d), enabling the rapid elimination of pores. When the depth of induction heating exceeds the thickness of the coatings, it can enhance the bonding strength between coatings and substrates [34]. It is important to note that induction heating is not suitable for non-conductive coatings. Additionally, the non-uniform heating characteristic of eddy currents may also lead to issues, such as stress concentration and grain coarsening in coatings due to local overheating, which requires further exploration and optimization. In conclusion, considering the advantages of electromagnetic induction heating, including high efficiency, operational flexibility, and controllable heating depth, it is expected to emerge as a new trend in developing coatings HT technologies.

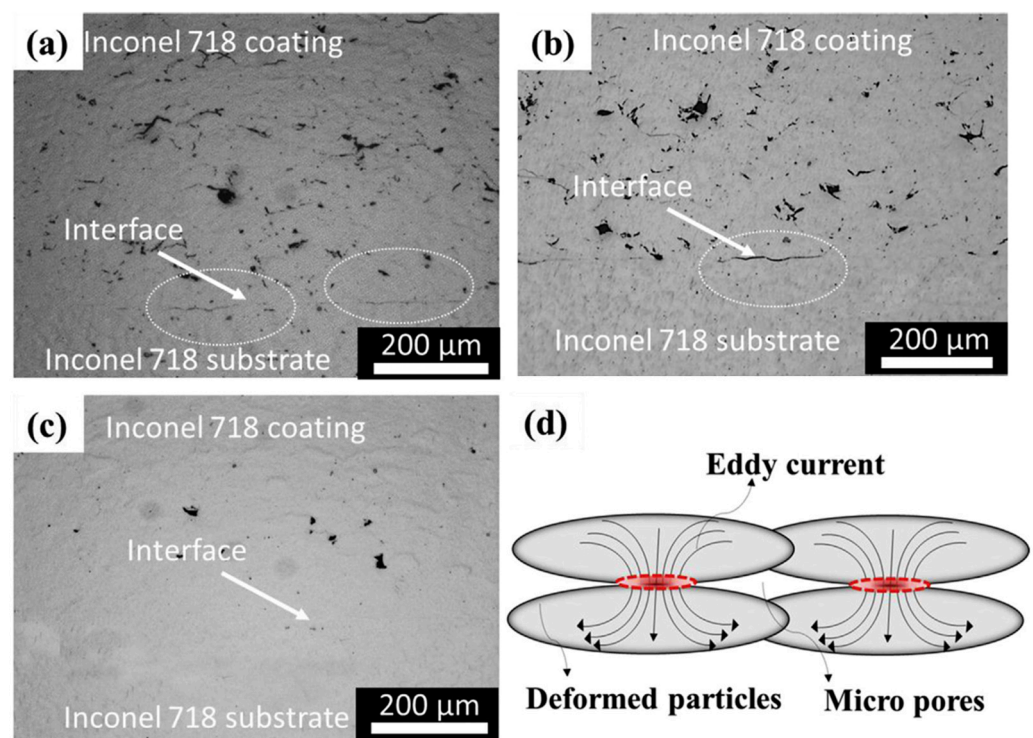


Figure 4. (a–c) Optical micrographs showing microstructures of cold sprayed IN718 coatings: (a) as-sprayed, (b) furnace heat-treated at 900 °C for 10 min, and (c) induction heat-treated at 900 °C for 10 min, and (d) schematic illustration of the eddy current flowing through deformed particles (adapted from reference [15], © Elsevier).

2.2. Laser Remelting

Selective laser melting (SLM), a powder bed-based additive manufacturing technology, fabricates three-dimensional components through layer-wise melting and solidification of metallic powder via high-energy laser beams. Laser remelting (LR) shares fundamental principles with SLM but specializes as a surface enhancement technique involving localized re-melting of deposited materials, where rapid laser-induced melting and solidification

of surface layers simultaneously eliminate porosity while developing refined microstructures [44,45]. Applied to CS coatings, LR enables surface fusion, pore sealing, and roughness reduction, offering distinct advantages, including precisely controlled melting depth and minimized thermal impact on substrates, thereby effectively enhancing mechanical, tribological, and other properties. Current research progress on LR post-processing for CS coatings is systematically summarized in Table 2.

Due to its loose and porous structure, the CS Ti coating cannot obtain the desired modification effect through conventional furnace heat treatment. After LR treatment of the CS Ti coating [45,46], the pores within a certain depth range on the surface are eliminated (Figure 5a). Commonly, three microstructure zones are formed in coatings after LR treatment, including the remelted zone (RZ), the heat-affected zone (HAZ), and the base material (BM) (Figure 5b,c). The particles undergo intense plastic deformation during the CS process, forming a lamellar structure in the BM zone. The heat input from the RZ zone influences the HAZ zone, and the grain growth coarsens the lamellar structure (Figure 5c). Due to rapid solidification after melting, the RZ zone forms a bimodal structure of fine α equiaxed grains and needle-like martensitic α grains (Figure 5b). Since the grains in the HAZ zone are coarse and the plastic deformation stress is released, its hardness is lower than that of the BM zone. Meanwhile, the RZ zone, with its fine grains and needle-like martensite, has the highest hardness. Furthermore, the formation of a hard oxide layer on the coating surface during LR treatment can enhance the coating's wear and corrosion resistance. However, it is important to note that excessive oxides can also reduce the coating's plasticity and fatigue resistance.

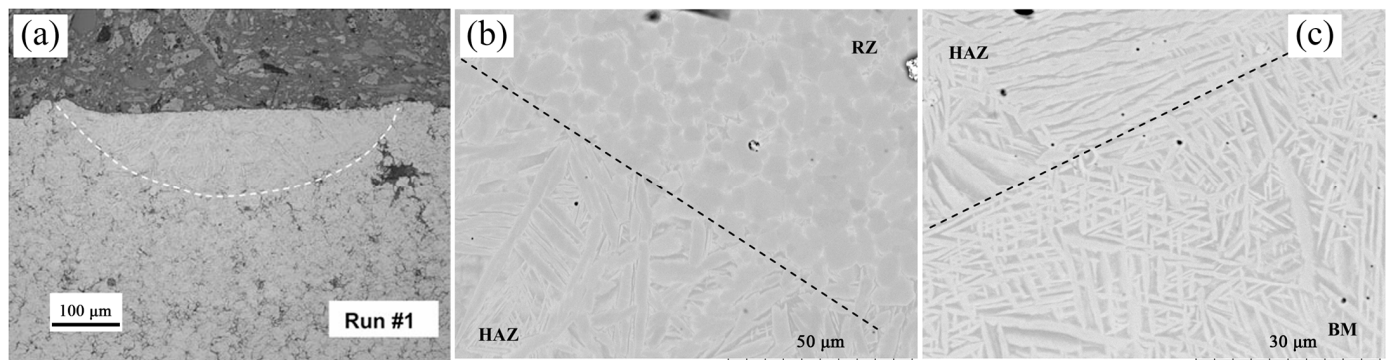


Figure 5. (a) Optical micrograph of the cross-section of cold sprayed Ti coating after laser remelting (adapted from reference [47], © Springer Nature). (b,c) SEM micrographs of cold sprayed Ti coating at different zones (adapted from reference [45], © Elsevier): (b) remelted zone (RZ); (c) base material (BM) and heat affected zone (HAZ).

Table 2. Effect of laser remelting on CS coatings.

References	Coatings	LR Parameters	Findings
[48]	Cu402F	Spot diameter: 4 mm Scan speed: 200 mm/s Laser power: 2500 W	LR retains the CS coating's original merits and accelerates the formation rate of the passivation film during the abrasion process, thereby significantly enhancing its abrasion resistance.
[49]	Cu402F	Spot diameter: 1 mm Scan speed: 500 mm/s Laser power: 2900 W	LR significantly improves the coating's corrosion resistance, which is attributed to the stable passivation film formed on the surface after a certain period, effectively protecting the internal structure.

Table 2. Cont.

References	Coatings	LR Parameters	Findings
[45,46]	Ti	Spot diameter: 2 mm Scan speed: 10–1000 mm/s Laser power: 220 W	Following LR, the remelting zone's hardness is significantly enhanced due to grain refinement and the formation of acicular martensite.
[47]	Ti	Spot diameter: 0.3–1.08 mm Scan speed: 21.6–48.3 mm/s Laser power: 440–1000 W	LR effectively eliminates pores within the coating and forms an oxide layer on its surface, thereby significantly enhancing the coating's corrosion resistance.
[50]	Ti	Spot diameter: 2 mm Scan speed: 50 mm/s Laser power: 200 W	LR formed a hard oxide layer on the coating's surface, altering the wear mechanism of the Ti coating from adhesive wear to abrasive wear, thereby significantly enhancing its wear resistance.
[51]	Ti-6Al-4V	Spot diameter: 1 mm Scan speed: 20 mm/s Laser power: 50–200 W	The surface roughness and hardness of the coating exhibit a positive correlation with the increase in laser power, consequently enhancing its wear resistance.
[52]	Ti/Cr ₃ C ₂	Spot diameter: 2.4 mm Scan speed: 20–100 mm/s Laser power: 0.5–2000 W	LR facilitated the reaction between Ti and Cr ₃ C ₂ , forming two new phases, β -Ti(Cr) and TiC _x , within the coating. This significantly enhanced the coating's hardness and wear resistance.
[30]	WC/Ti	Spot diameter: 3.8 × 1.2 mm Scan speed: 8 mm/s Laser power: 200–800 W	LR effectively improves the coating's sliding wear resistance, which is attributed to the formation of the hard TiC phase.
[53]	Al	Spray distance: 250 mm Spot diameter: 5 mm Laser power: 800 W Argon gas speed: 8 L/min	After undergoing LR, the coating's initially porous structure becomes densified, the grain size is significantly reduced, and the hardness and wear resistance are markedly enhanced.
[44]	Al	Spray distance: 250 mm Spot diameter: 5 mm Laser power: 800 W Argon gas speed: 8 L/min	Following LR, the coating's residual compressive stress increased by 26%, enhancing the bonding strength between the coating and the substrate. This improvement effectively prevents coating delamination.
[54]	Al/Si	Spot diameter: 40 μ m Scan speed: 1000 mm/s Laser power: 200–300 W	LR densifies the coating, refines its structure, and significantly reduces surface roughness.
[55]	IN625	Heat input: 14–28 J/mm Scan speed: 25–50 mm/s Laser power: 700 W	LR decreases the coating's porosity and enhances its elastic modulus. However, the columnar dendrite structure developed in the remelting layer reduces the coating's hardness.
[56]	316L	Spot diameter: 1.4 mm Scan speed: 100 mm/s Laser power: 500 W	LR significantly reduces the coating's porosity, exhibits minimal thermal impact on the substrate, and markedly enhances its corrosion resistance.

Khun et al. [51] discovered that increasing the laser power would augment the surface roughness of CS coatings, which was attributed to the protrusions and depressions that emerged after surface remelting. Increased laser power expanded the temperature gradient between the coating and substrate. The high cooling rate allowed the coating to obtain higher hardness, which also caused more cracks in the coating, leading to increased brittleness. Research indicated [45,46] that an overly low laser scanning speed would cause the coating material to vaporize and generate cracks and pores after the solidification of the remelted layer. In contrast, an excessively high laser scanning speed would make it challenging to eliminate the defects of the coating. The depth of the molten pool can be determined by the empirical relationship $H = (P/(DV))^{1/2}$ [47]. Here, the depth H of a molten pool increases with the elevation of laser power P . When the laser power reaches a certain value, the coating and substrate are melted, impacting their bonding strength. In conclusion, the laser power and the scanning speed can alter the heat input of LR to the coating within a unit of time. In practical applications, reasonable parameters should be designed based on the characteristics of the coating to obtain the desired remelting effect.

LR is capable of enhancing the corrosion behavior of CS coatings. It can be observed from Figure 6 that, in contrast to the as-sprayed state, the open circuit potential (OCP) and corrosion potential (E_{corr}) values of the LRed Ti coating have undergone a significant positive shift, and the corrosion current density (I_{corr}) has decreased significantly, both being similar to those of bulk Ti. This implies that the LR treatment has notably improved the corrosion resistance of the Ti coating, which might be related to the effective protection of the internal structure provided by the barrier effect of the remelted layer and the oxide layer [47]. The data suggest that the corrosion resistance of the LRed Ti coating is close to that of bulk Ti. Still, the curve characteristics differ, indicating that the corrosion behaviors of the two materials are inconsistent. The mechanism through which the unique microstructure and oxide layer of the LR coating influence its corrosion resistance merits further investigation.

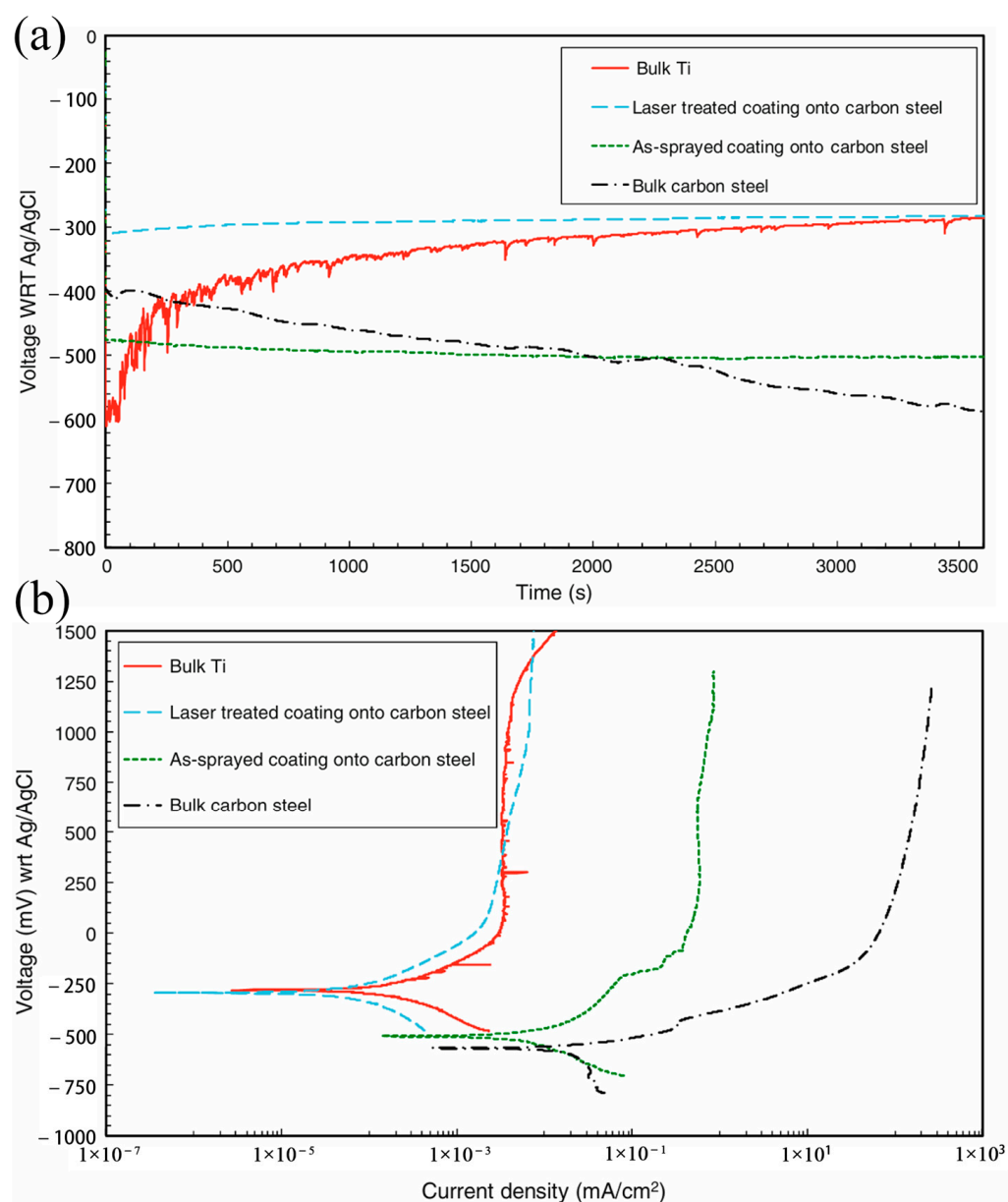


Figure 6. (a) Open circuit potentials (OCPs) and (b) potentiodynamic polarization scans of bulk Ti, carbon steel, as-sprayed Ti coating (on carbon steel), and laser-treated Ti coating measured in an aerated 3.5% NaCl solution (adapted from reference [47], © Springer Nature).

Apart from the aforementioned pure metals or alloys, LR can also be utilized in post-treatment CS metal–non-metal composite coatings. After the deposition of the composite materials using CS, the LR post-treatment not only eliminates the coating defects but also accompanies the formation of new phases, attaining superior modification outcomes. Shikalov et al. [52] employed LR to modify the microstructure of CS Ti–Cr₃C₂ composite coating. During the remelting process of the coating, Ti and Cr₃C₂ reacted to generate the β -Ti(Cr) and TiC_x phases. TiC_x, as a hard and wear-resistant phase, was dispersed within the β -Ti(Cr) solid solution strengthening phase; the new microstructure significantly increased the hardness and wear resistance of the coating. This research proved the feasibility of fabricating hard and wear-resistant titanium-based metal–ceramic coatings through the CS + LR process. Furthermore, after the LR treatment of CS Al–Si composite coating [54], the microstructure was significantly refined, and the surface roughness was effectively reduced. Nevertheless, issues such as the low deposition efficiency of Si particles and the tendency to form large pores between the remelted and unmelted layers still exist, and further exploration is needed for effective solutions.

3. Mechanical Processing

3.1. Friction Stirring

Friction stir welding (FSW) enables the joining of dissimilar materials through frictional interaction between a rotating tool and workpiece, where the material undergoes localized melting [57]. As a novel and efficient solid-state processing technique derived from FSW, friction stir processing (FSP) demonstrates significant potential in fabricating ultrafine-grained structures and metal matrix surface nanocomposites [58,59]. In FSP operations, a rigid rotating tool with specialized geometry initially penetrates the material surface before traversing along predetermined paths (Figure 7a). The tool–material interaction generates substantial frictional and plastic deformation heating, inducing material softening and complex flow patterns that collectively form a stirring zone [60,61]. This technique shows particular promise for enhancing CS coatings through microstructural homogenization, defect elimination, and improved coating–substrate interfacial bonding. Current research advancements in FSP applications for CS coatings are summarized in Table 3.

The surface morphology of the CS coating after FSP is depicted in Figure 7b. It can be discerned that a severe flash has emerged on the trailing side of the wear scar, and a keyhole was left on the coating surface after the tool was withdrawn, which is analogous to the FSW process [62]. The heat generated by the low rotational speed and high traverse speed fails to fully soften and induce plastic deformation flow of the material, increasing surface roughness. The surface of the coating becomes smoother as the rotational speed of the tool increases. Likewise, at the same rotational speed, the slower the tool traverse speed is, the smoother the coating surface [63]. Under most circumstances, the FSP stirring zone can be classified into the advancing side, the pin zone, and the trailing side (Figure 7c). The thickness in the middle of the stirring zone is conspicuously reduced, while the thickness on both sides exhibits little variation. It is notable that a portion of the deposits on the surface of the advancing side will be incorporated into the matrix under the tool's stirring effect. Although the coating undergoes severe plastic deformation during the FSP process, no spalling failure occurs.

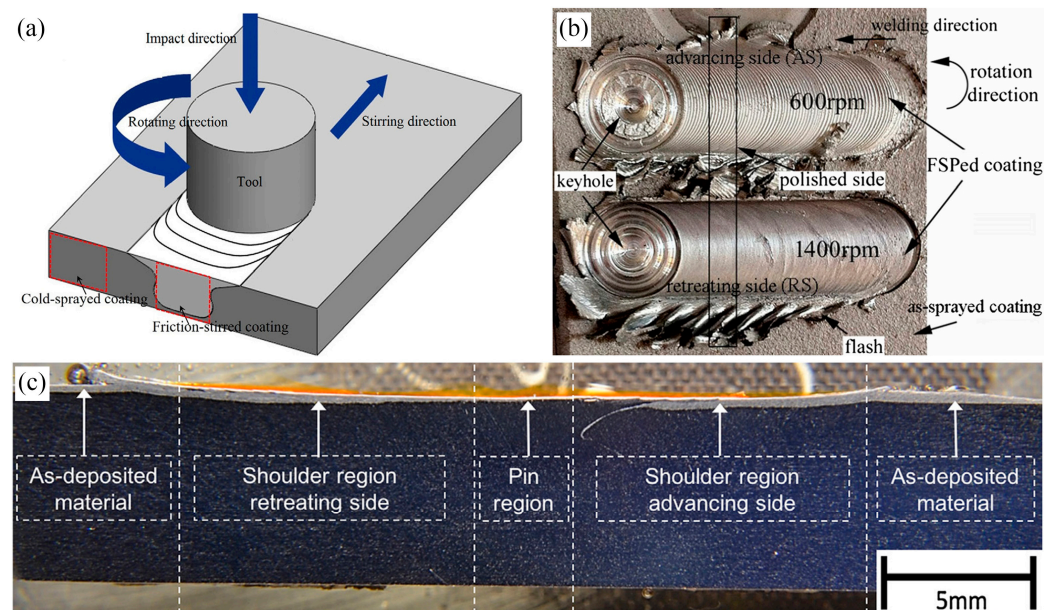


Figure 7. (a) Schematic diagram of FSP on cold sprayed coatings (adapted from reference [64], © Elsevier) (b) General morphologies of as-sprayed Si/5056Al coating after FSP at 600 rpm or 1400 rpm (adapted from reference [65], © Springer Nature) (c) Cross-section view of the cold sprayed coating after FSP (adapted from reference [66], © Elsevier).

Table 3. Effect of friction stir processing on CS coatings.

References	Coatings	FSP Parameters	Findings
[67]	Al	Stir tool material: H13 steel Shoulder diameter: 16 mm Concave shoulder angle: 2.5° Rotation speed: 1500 rpm Traverse speed: 9–18 mm/min	After the coating underwent FSP treatment, its conductivity was markedly enhanced due to defect elimination. Additionally, the bonding strength between the coating and the substrate was significantly improved due to intermetallic compound formation.
[68]	Al	Stir tool material: H13 steel Shoulder diameter: 16 mm Rotation speed: 2100–3000 rpm Traverse speed: 1 mm/min	FSP markedly enhances the coating's corrosion resistance. The formation of the $\text{Al}_{12}\text{Mg}_{17}$ intermetallic compound leads to a substantial improvement in coating hardness.
[69]	AA7075	Stir tool material: H13 steel Shoulder diameter: 12 mm Concave shoulder angle: 3° Pin diameter: 1.7 mm Pin height: 1.5 mm Rotation speed: 1120 rpm Traverse speed: 22.4 mm/min	After FSP, the coating's hardness increased more than threefold owing to the refined grain structure, enhanced material mixing, and strengthened bonding between the coating and the substrate.
[70,71]	AA2024/ Al_2O_3	Stir tool material: H13 steel Shoulder diameter: 10 mm Concave shoulder angle: 2.5° Pin diameter: 3.4 mm Pin height: 2.9 mm Rotation speed: 1500 rpm/900 rpm Traverse speed: 100 mm/min//50 mm/min	FSP refines and disperses the Al_2O_3 particles within the coating, significantly enhancing its tensile properties. Additionally, by improving the coating's surface condition, FSP also enhances its corrosion resistance.
[65,72]	SiC/5056Al	Shoulder diameter: 10 mm Concave shoulder angle: 2.5° Pin diameter: 3.4 mm Pin height: 2.9 mm Rotation speed: 600–1400 rpm Traverse speed: 100 mm/min	FSP significantly enhances the coating's density, refines the Al matrix grains into fine equiaxed crystals, and fully fractures and evenly disperses the SiC particles. This process consequently improves the coating's hardness and wear resistance.

Table 3. Cont.

References	Coatings	FSP Parameters	Findings
[73]	6061Al/CoCrFeNi	Stir tool material: H13 steel Shoulder diameter: 18 mm Concave shoulder angle: 2.5° Pin diameter: 7 mm Pin height: 3.8 mm Rotation speed: 1200 rpm Traverse speed: 45 mm/min Shoulder diameter: 10 mm Concave shoulder angle: 2.5°	After FSP treatment, the pores within the coating are eliminated, and the reinforced particles attain full metallurgical bonding with the matrix. Consequently, the coating's tensile strength and ductility are significantly enhanced.
[64]	Cu60-Zn40	Pin diameter: 3.4 mm Pin height: 1.5 mm Rotation speed: 1500 rpm Traverse speed: 100 mm/min	After FSP, the coating predominantly consists of high-angle grain and twin boundaries, substantially increasing tensile strength.
[74]	Cu-10Ti ₃ SiC ₂	Shoulder diameter: 9 mm Rotation speed: 500–700 rpm Traverse speed: 50 mm/min	FSP significantly refines the coating's grain structure, enhances the bonding between the coating and the substrate, and improves its electrical conductivity, tensile strength, and ductility.
[75]	Al-Cu-Ni	Concave shoulder angle: 1.1–1.5° Rotation speed: 600–1200 rpm Traverse speed: 100–1200 mm/min	FSP substantially enhanced the homogeneity and phase composition of the coating, resulting in the formation of two new phases: AlNi and Al ₂ Cu. Additionally, the integrity of the FSP-treated coating surpassed that of the LR-treated coating.
[76]	CuAlNi/Al ₂ O ₃	Stir tool material: WC Shoulder diameter: 10 mm Rotation speed: 360 rpm Traverse speed: 20 mm/min	FSP can substantially refine the coating's grain structure and ensure a uniform distribution of Al ₂ O ₃ particles, thereby significantly enhancing the coating's elastic modulus, hardness, and sliding wear resistance.
[77]	Ti	Stir tool material: WC Shoulder diameter: 12 mm Concave shoulder angle: 2.5° Rotation speed: 900 rpm Traverse speed: 63 mm/min	FSP can achieve full coating densification, with grain refinement to less than 1 µm. The coating hardness reaches up to 700 HV, seven times higher than that of the sprayed coating.
[78]	Ni50-Ti50	Stir tool material: W-Re Shoulder diameter: 15 mm Concave shoulder angle: 2.5° Rotation speed: 1500 rpm Traverse speed: 100 mm/min Shoulder diameter: 10 mm Concave shoulder angle: 2.5°	Following the FSP process, an array of intermetallic compounds was generated, substantially enhancing the coating's hardness and wear resistance.
[63]	Ni-Nb-Si	Pin diameter: 3 mm/6 mm Pin height: 2.7 mm Rotation speed: 500 rpm Traverse speed: 30 mm/min// 50 mm/min	FSP can significantly improve the composite coating's corrosion resistance in molten glass, benefiting from the densification and alloying of the materials.
[61]	Diamalloy 1003 (Similar to 316L)	Stir tool material: WC Shoulder diameter: 15 mm Concave shoulder angle: 1.5° Pin diameter: 4 mm Pin height: 1.4 mm Rotation speed: 300 rpm Traverse speed: 50 mm/min Stir tool material: W-Re/pcBN Shoulder diameter: 18 mm/25.4 mm Concave shoulder angle: 2°/0°	The coating underwent complete recrystallization during the FSP process, eliminating defects such as pores and cracks. This led to the formation of a dense and uniform fine-grained microstructure.
[79]	WC-CoCr/Al ₂ O ₃	Pin diameter: 5 mm Pin height: 5.7 mm/5.75 mm Rotation speed: 250 rpm/800 rpm Traverse speed: 100 mm/min// 76 mm/min	FSP facilitates the uniform dispersion of deposited WC-CoCr aggregates and refines Al ₂ O ₃ particles, enhancing the homogeneity of coating hardness and corrosion resistance.

FSP can enhance the interparticle bonding mechanism in CS coatings and refine the grains. After undergoing FSP, the bonding mechanism between 5056Al particles in the CS SiC/5056Al composite coatings [65] transforms from mechanical to metallurgical bonding, increasing the bonding strength. FSP elevates the proportion of high-angle

grain boundaries (HAGBs) in the microstructure of the CS Cu-Zn alloy coatings [64] from 22.6% to 90.5%, and HAGBs are directly associated with the formation of new grains, suggesting that dynamic recrystallization takes place during the FSP process. Dislocations and low-angle grain boundaries (LAGBs) accumulate continuously throughout FSP and are converted into HAGBs through dislocation rearrangement and grain rotation. A considerable number of HAGBs can effectively impede dislocation movement, thereby enhancing the work-hardening capacity of the coating. Additionally, the grain refinement during the recrystallization process can augment the coating's tensile strength, and the sliding of HAGBs and related movements can offer relatively reasonable plasticity while reducing the coating's anisotropy.

In most circumstances, FSP can conspicuously enhance the hardness of CS coatings. For single-component metal or alloy coatings, it is mainly attributed to grain refinement and microstructure densification. For binary or multi-component metal composite coatings, it also benefits from the formation of intermetallic compounds and the homogenization of composition. For ceramic-reinforced metal matrix composite coatings, it is mainly ascribed to the refinement and uniform dispersion of ceramic particles, as well as the improvement of the bonding strength between ceramic and metal particles. Nevertheless, considering that the high temperature generated during the FSP process may cause the release of residual stress and abnormal grain growth in the surrounding area [61], when these factors predominate, the hardness of the coating will conversely decrease, which may deteriorate its wear resistance. How to alleviate the softening effect of FSP on the coating merits further investigation.

Owing to the intense thermo-mechanical effect during the FSP process, phase transformation in the coating can be triggered even when the temperature is lower than the melting point of the material. Huang et al. [64] examined the phase evolution of CS Cu-Zn alloy coatings during FSP. The results indicated that the microstructure of the CS coating (Figure 8a) was dominated by the α phase (red), with a small quantity of the intermetallic compound β' phase (yellow) distributed. After FSP (Figure 8b), the thermo-mechanical effects led to the transformation of some of the α phase into the β'' phase and the non-equilibrium γ phase (Cu_5Zn_8 , blue). The alteration in phase composition enhanced the tensile strength of the coating, but the precipitation of β'' and γ phases resulted in a very limited elongation at break. Furthermore, thermal effect is prone to cause coarsening of grains in the substrate [69]. Notably, for some heat-sensitive materials, the potential adverse impacts of the thermal effect of FSP should be thoroughly considered.

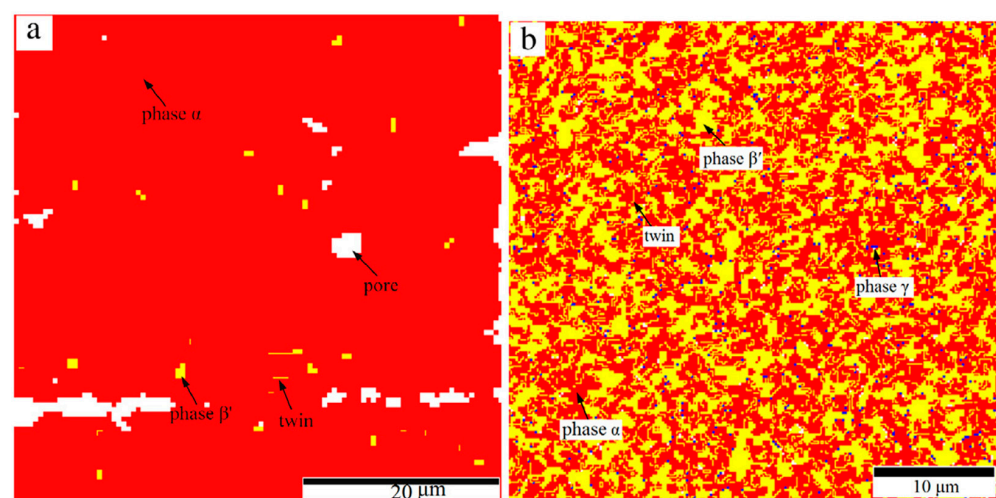


Figure 8. EBSD phase maps of (a) as-sprayed and (b) friction-stirred coatings (adapted from reference [64], © Elsevier).

CS metal matrix composites (MMCs) are inherently brittle due to weak interparticle bonding and plastic loss, thereby restricting their application. Owing to the intense mixing effect of FSP, the microstructure and properties of MMC coatings can be effectively enhanced. Research has indicated that after FSP, the hardness, tensile strength, and elongation of CS AA2024/Al₂O₃ composite coating [70,71] have all been elevated, attributed to the enhanced bonding strength between AA2024 particles and the dispersion strengthening effect of refined Al₂O₃ particles. The corrosion resistance of the coating is significantly improved as a result of the improved surface condition. However, with the increase in FSP passes, the deterioration of the internal structure will reduce its corrosion resistance. Yang et al. [74] aimed to improve the comprehensive performance of CS Cu-10Ti₃SiC₂ composite coating using FSP. Studies have demonstrated that FSP effectively reduces defects such as pores and cracks in the coating and closes the particle interfaces. This enables the coating to achieve higher electrical conductivity while enhancing the tensile strength and elongation. Notably, due to the shape and movement characteristics of the tool, it may cause significant differences in the number of reinforcing particles in the advancing side, pin zone, and retreating side [72], which will lead to inhomogeneity in the mechanical and tribological properties of the stirred zone.

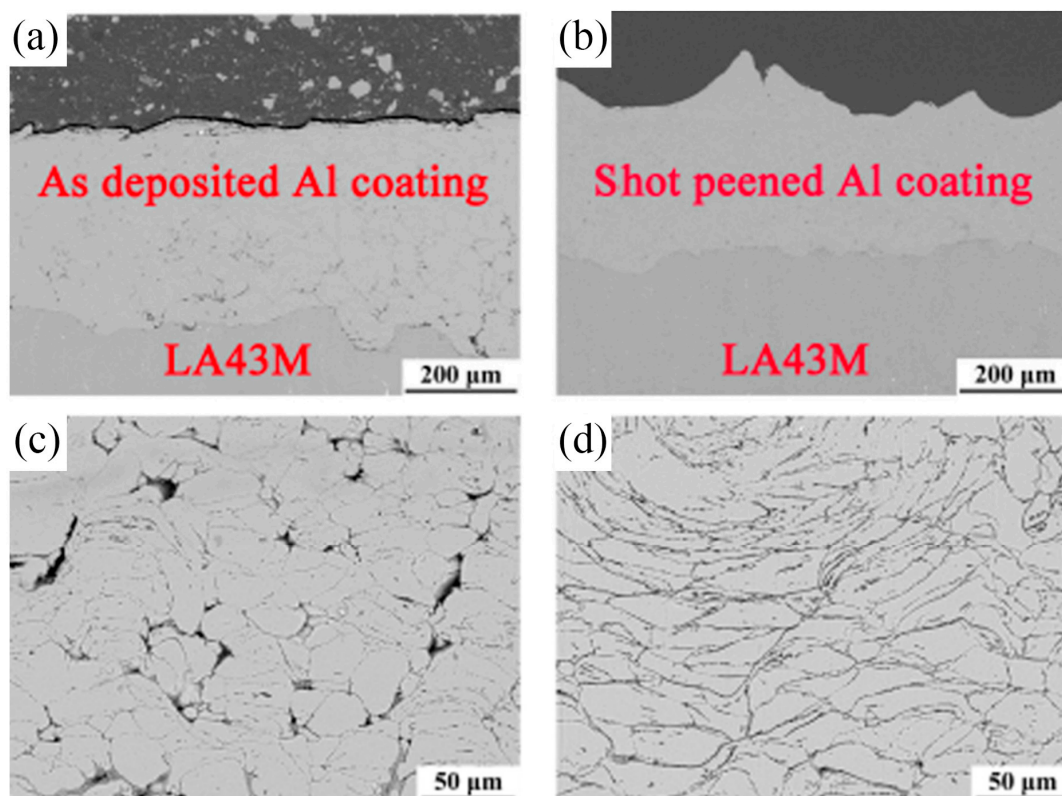
3.2. Shot Peening

When preparing coatings with considerable thickness using CS, the coatings are highly susceptible to residual stress due to the non-uniform stress distribution and structural constraints during the deposition process. In severe cases, it may lead to the separation of the coating from the substrate [80,81]. Shot peening (SP) is a technique that accelerates shot pellets of a certain hardness using gas and impacts the workpiece, thereby modifying its surface. In principle, the surface of the workpiece absorbs the kinetic energy of shot pellets and generates a plastic deformation layer and beneficial residual compressive stress [82]. Some researchers have employed the SP technology for post-treatment of CS coatings. The related research is listed in Table 4.

SP can induce further plastic deformation of the particles within the CS coatings, which is conducive to enhancing the surface morphology and internal microstructure of coatings. Lu et al. [83] implemented the strengthening treatment of the CS Al coating using SP. The outcomes demonstrated that the untreated coating was distributed with numerous pores (Figure 9a,c). After being constantly impacted by high-energy pellets, pits emerged on the surface, and the internal particles were severely flattened; the microstructure densified as most of the pores were eliminated (Figure 9b,d). Additionally, dynamic recrystallization can occur in the particles during the CS process [84], forming many ultrafine grains at the particle interfaces. It is widely acknowledged that nanocrystalline materials display exceptional properties compared to general bulk materials. For instance, 304 stainless steel [85] formed 40-nm ultrafine austenite grains on the surface after SP, significantly enhancing both tensile strength and fracture toughness. Regrettably, no research reports have been discovered regarding the formation of ultrafine grains in CS coatings induced by SP post-treatment. Utilizing SP to promote the formation of more nanocrystals in CS coatings might be advantageous for optimizing mechanical, wear, and corrosion properties.

Table 4. Effect of shot peening on CS coatings.

References	Coatings	SP Parameters	Findings
[82]	Al//Al/Al ₂ O ₃	Ball material: S230 cast iron Diameter: 0.6 mm Stand-of-distance: 380 mm Pressure: 0.15 MPa Exposure time: 33 s Coverage: 200%	SP can effectively harden the coating's surface; however, it has minimal impact on the residual stress state within the coating.
[83]	Al	Ball material: 1Cr18 ss Diameter: 0.25–0.33 mm Stand-of-distance: 20 mm Pressure: 1 MPa	After the SP, the coating's porosity is reduced to merely 0.2%. The coating's densification significantly enhances its corrosion resistance.
[86]	6082Al	Ball material: S230 cast iron Diameter: 0.6 mm Coverage: 100% and 800%	SP does not enhance the coating's fatigue strength further. Initial cracks under fatigue loading originate from the damage inflicted by SP on the coating.
[87]	Zn	Ball material: 1Cr18 ss Diameter: 0.2–0.3 mm Stand-of-distance: 80 mm Pressure: 0.05–0.2 MPa Exposure time: 600 s Coverage: 200%	SP significantly enhances the coating's density, leading to a substantial increase in hardness and a twofold improvement in corrosion resistance compared to spray coatings.
[88]	Ti-6Al-4V	Ball material: S100 steel Diameter: 0.3 mm Pressure: 0.0689–0.4137 MPa	SP decreases the porosity of the coating surface. The surface hardness improves as the shot peening pressure increases, enhancing its resistance to abrasive wear.
[89]	NiCrAlY	Ball material: Glass bead grit Diameter: 0.3 mm Stand-of-distance: 150 mm Pressure: 0.3 MPa	By decreasing the coating's surface roughness, SP facilitates the development of a homogeneous protective oxide film during post-treatment, thereby significantly enhancing the coating's oxidation resistance.

**Figure 9.** Microstructural characterization: (a,b) cross-sectional microstructure and (c,d) etched cross-sectional microstructure of pure Al-coated LA43M and shot-peened pure Al-coated LA43M, respectively (adapted from reference [83], © Elsevier).

When CS fabricates coatings, the introduction of residual stress is unavoidable. Residual stress is a crucial factor for obtaining dense and highly adherent coatings and significantly influences the coatings' durability [80]. Ghelichi et al. [82] discovered that the effect

of SP treatment on optimizing the residual stress state of CS Al coating was not prominent. The surface residual stress and the depth of compressive stress merely decreased and increased slightly, respectively (Figure 10), mostly resulting in surface work hardening of the coating. Additionally, Moridi et al. [86] found that conventional SP treatment would inflict damage on the coating and fail to enhance the fatigue strength of the coating. This is because there are numerous unbonded or weakly bonded particles in CS coatings, which leads to the majority of the kinetic energy of shots being utilized to remove surface materials. Thus, they are unable to transfer residual compressive stress to deeper regions of the coating. In contrast, conducting SP pretreatment of the substrate before CS can yield better strengthening effects, increasing fatigue strength by 26%. Therefore, for CS coatings of diverse materials, thicknesses, and areas, more rational SP parameters, such as the diameter, velocity, and flow rate of the shot, as well as the shot angle, time, and coverage rate, or multiple shot peening using “gradient parameters” can be further explored to reduce the generation of surface cracks and material delamination during the SP process.

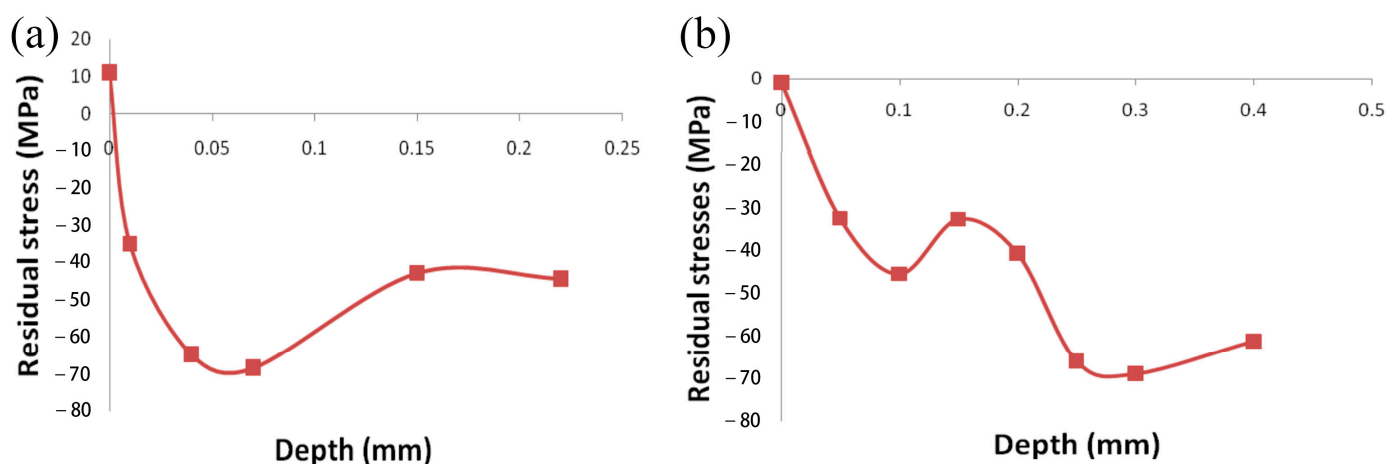


Figure 10. In-plane stress distributions in the cold sprayed Al coating (a) before and (b) after shot peening (adapted from reference [82], © Tech Science Press).

In recent years, another highly efficient shot peening technology, namely ultrasonic shot peening (USP), has begun to attract attention. Slightly different from SP, USP employs ultrasonic waves at 20 kHz or above to drive the pellets in the chamber to repeatedly strike the target surface [90], achieving surface modification of the material by inducing residual compressive stress at high frequencies. Zhang et al. [91] were the pioneers who reported the influence of USP on the microstructure and corrosion resistance of CS Cu coating. The findings indicated that USP formed a dense layer of approximately 100 μm on the surface of the Cu coating, reducing the porosity from 4.1% to 0.52%, and no new cracks were observed, which might also be attributed to the excellent plasticity of pure Cu. Benefiting from the dense layer formed on the coating surface by USP, the I_{corr} value decreased by more than two orders of magnitude, attaining good corrosion resistance. Furthermore, the research conducted by Takeda et al. [92] demonstrated that USP could significantly enhance the fatigue life of TiNi shape memory alloys, which was associated with the work hardening of the material and the formation of residual compressive stress. Currently, the post-treatment of CS coatings predominantly employs conventional gas-driven shot peening, yet conventional shot peening is prone to introducing new cracks in the coating [82,86]. For bulk materials, the USP technology has been successfully utilized in the fabrication of ultrafine-grained surfaces of low-carbon steel [93], copper [94], and aluminum [95], among others. Notably, for some workpieces with complex shapes, the randomness of pellets during the application of USP may give rise to issues such as non-

uniform coverage [90]. In conclusion, USP is a highly promising novel post-treatment technology for CS coatings; more research reports are anticipated to emerge soon.

4. Thermo-Mechanical Processing

Hot Rolling

Metal composite plates can obtain excellent comprehensive performance by coordinating the properties of different materials. However, how to economically and efficiently fabricate high-quality metal composite plates is an urgent problem that needs to be solved at present [96–98]. Hot rolling (HR) is a process in which metals are heated above the recrystallization temperature and then rolled to induce plastic deformation [99]. It is highly mature in the industry at present. In recent years, some researchers have developed a novel fabrication process for metal composite plates, including CS + HR, which is expected to address the problems above. Relevant studies are listed in Table 5.

Table 5. Effect of hot rolling on the CS metal composite plates.

References	Coatings/Substrates	HR Parameters	Findings
[100]	Ti/Steel	Heating: 1000 °C for 10 min Rolling speed: 20 mm/s Rolling reduction ratio: 50% Rolling pass: 1 Type of cooling: air cooling	HR eliminates the Ti/Ti particle interface, and the IMC diffusion layer is formed at the Ti/Steel interface to realize metallurgical bonding. The composite plate's UTS, SBS, and EL have also been improved.
[101]	Ti/304SS	Heating: 850, 950, 1050 °C for 5 min Rolling pass: 2 Type of cooling: air cooling	HR densifies the structure of Ti coating and strengthens the interface bonding of composite plate. Its corrosion resistance improves the level of common CP Ti, which is better than 304 SS.
[102]	TA2/Q235	Heating: 850 °C for 5 min Rolling reduction ratio: 50%	After HR, the TA2/Q235 interface formed a nano-thickness TiC layer, which inhibited the formation of FeTi and Fe ₂ Ti. UTS and EL reached 560 MPa and 32%, respectively.
[98]	7075Al/AZ31B Mg	Heating: 400 °C for 1 min Rolling speed: 20 mm/s Rolling reduction ratio: 20% Rolling pass: 1	The shear strength of Al/Mg composite plates decreased slightly after HR, which was attributed to forming a brittle IMC layer at the Al/Mg interface.
[103]	B ₄ C-6061Al/6061Al	Heating: 500 °C for 2 h Rolling speed: 0.3 m/s Rolling reduction ratio: 20% Rolling pass: 1	HR can improve the binding between B ₄ C and 6061 Al particles, promote the uniform distribution of B ₄ C particles, and significantly improve the coating's wear resistance.

Figure 11 depicts the microstructure and elemental distribution of the AZ31B Mg substrate and CS 7075 Al coating both before and after hot rolling. It is observable that the particles in the CS coating are conspicuously flattened. Mechanical interlocking exists at the interface between the coating and the substrate (Figure 11a), suggesting that severe plastic deformation occurs when the particles collide with the substrate. No diffusion layer or IMC was formed due to the low temperature and extremely short collision duration in the CS process (Figure 11b). During the HR process, the interface became relatively smooth under mechanical action (Figure 11c). The preheating treatment before rolling offered the driving force for the diffusion of elements between the coating and the substrate (Figure 11i) and the formation of IMC (Figure 11j). Nevertheless, the specimens' shear bond strength (SBS) in different directions declined after HR, which was associated with the weakened mechanical interlocking effect of forming a new interface [98]. Additionally, the brittle IMC layer fractured as it was incapable of withstanding intense plastic deformation, thereby presenting a banded distribution in the RD (rolling direction) (Figure 11c), which is highly disadvantageous for SBS in this direction since the discontinuous IMC layer is prone to rotation and fracture when subjected to shear forces [98].

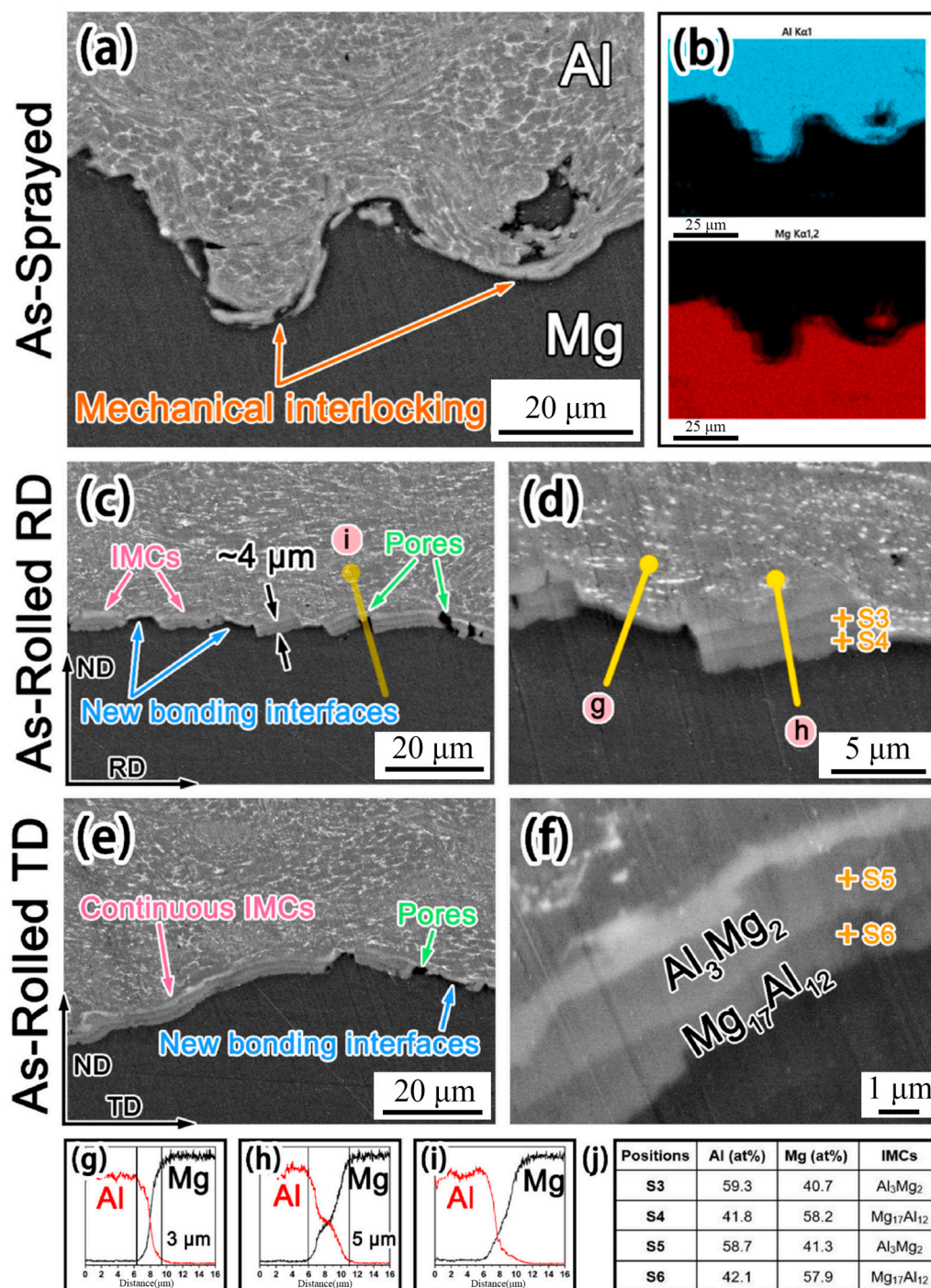


Figure 11. Cross-sectional SEM images of as-sprayed (a) and as-rolled Mg/Al composite plates in the ND-RD (c,d) and ND-TD (e,f) planes, respectively. Panel (b) shows the EDS mapping result for panel (a). Panels (g–i) show the EDS line scans performed across the new bonding interface, IMCs, and pores. Panel (j) summarizes point analysis results for panels (d,f) (adapted from reference [98], © Elsevier).

In the HR process, the temperature and reduction ratio significantly determine the ultimate quality of the sheet. In the study by Ren et al. [104], the ultimate tensile strength (UTS) and elongation (EL) of the CS Mg/Al composite sheet exhibited a positive correlation with the rolling temperature and reduction ratio, attributed to the combined effects of improved interparticle bonding within the Al coating and grain refinement of the Mg substrate. Nevertheless, a high rolling temperature can lead to the broadening of the IMC layer, facilitating the initiation and propagation of cracks at the brittle IMC, which severely

reduces the SBS of the composite sheet. At 350 °C and 400 °C, increasing the rolling reduction ratio can notably enhance the SBS of the composite sheet. Ren et al. [104] opined that this might be associated with the increase in the proportion of newly formed bonding interfaces and the reduction in the number of micropores. However, raising the rolling reduction ratio implies that the sheet has to endure a greater amount of plastic deformation, which elevates the risk of edge cracking in the composite sheet. It is worth mentioning that after hot rolling, metal composite sheets, when accompanied by appropriate annealing treatment [105], can effectively increase EL without sacrificing the original UTS, ensuring that the sheet possesses excellent formability during subsequent processing.

It is commonly held that [106] introducing ceramic particles is conducive to enhancing the wear resistance of CS Al-based coatings. Nevertheless, owing to the relatively low bonding strength between ceramic and metal particles in the coating [107] and the propensity of the coating to detach from the substrate under external forces [108], it remains challenging to fabricate highly wear-resistant ceramic/metal composite coatings merely using CS at present. Research has indicated [109] that hot rolling is beneficial for achieving metallurgical bonding between the coating and the substrate. Jiang et al. [103] conducted post-treatment on CS B₄C/6061Al composite coating utilizing HR. The results demonstrated that the coating underwent dynamic recrystallization under the combined action of heat and mechanical forces, defects were effectively remedied, the distribution of B₄C particles was homogenized, and the bonding strength between the coating and the substrate was increased twice. In sliding wear tests, the wear rate of the rolled composite coating was merely 40% of that of the 6061Al substrate; its wear resistance was conspicuously enhanced. Furthermore, this research group [110] also successfully repaired the defects of neutron shielding B₄C/6061Al composite plates utilizing the CS + HR process; the strength of the repaired material was comparable to that of the in-service plates, further broadening the application potential of CS in the field of repair.

5. Chemical Processing

Chemical Conversion Coating

Chemical conversion coating (CCC) represents an effective corrosion inhibition treatment approach for the surfaces of light alloys. The active metal surface is passivated through chemical reactions in a chemical bath or by spraying solutions (commonly chromate-, phosphate-, and permanganate-based solutions) onto the components. Due to its favorable economic benefits and operational simplicity, it has emerged as the preferred solution in the industrial field [111,112]. Many research reports on CCC for forged aluminum alloys are available; however, investigations into the interaction between CCC and CS deposits remain scarce. Relevant studies have been listed in Table 6.

Figure 12 presents the microstructural morphologies of forged 2024 alloy (W2024) and cold sprayed 2024 alloy (CS2024) before and after treatment with chromate-based conversion agents. It can be observed that IMCs exist in both types of 2024 Al (the white highlighted areas in Figure 12a,b). The rapid solidification of particles during the atomization process results in a reticular distribution of IMCs in the CS deposits. The CCC on both W2024 and CS2024 displays mud crack characteristics, which is attributed to the dehydration of the coating in the high vacuum environment of the SEM [113]. The pits on W2024 (Figure 12c) were not formed during the CCC process but were caused by the dissolution and detachment of IMCs during the chemical cleaning pretreatment before CCC. EDS elemental line scanning results indicate that the contents of Cr and O elements in the IMC regions are relatively low (Figure 12e,f). The presence of chromium hydroxide in the chromate conversion coating leads to a correlation in the distribution of Cr and O elements, suggesting that the coatings formed by CCC in these regions are relatively thin,

which is due to the hindrance effect of Cu-containing IMCs on the nucleation and growth of CCC [114]. Kim et al. [114] contend that the formation mechanisms of CCC on W2024 and CS2024 are consistent. The dissimilarity in IMC shape distribution and the preferential corrosion at the interfaces between particles are the primary causes of the morphological differences in CCC.

Table 6. Effect of chemical conversion coatings on CS coatings.

References	Coatings	CCC Parameters	Findings
[114]	2024Al	Transforming agents: Alodine 1201 Span: 3 min	The corrosion expansion caused by the unique morphology of CCC on CS2024 is the primary cause of its sharp decrease in corrosion resistance with time.

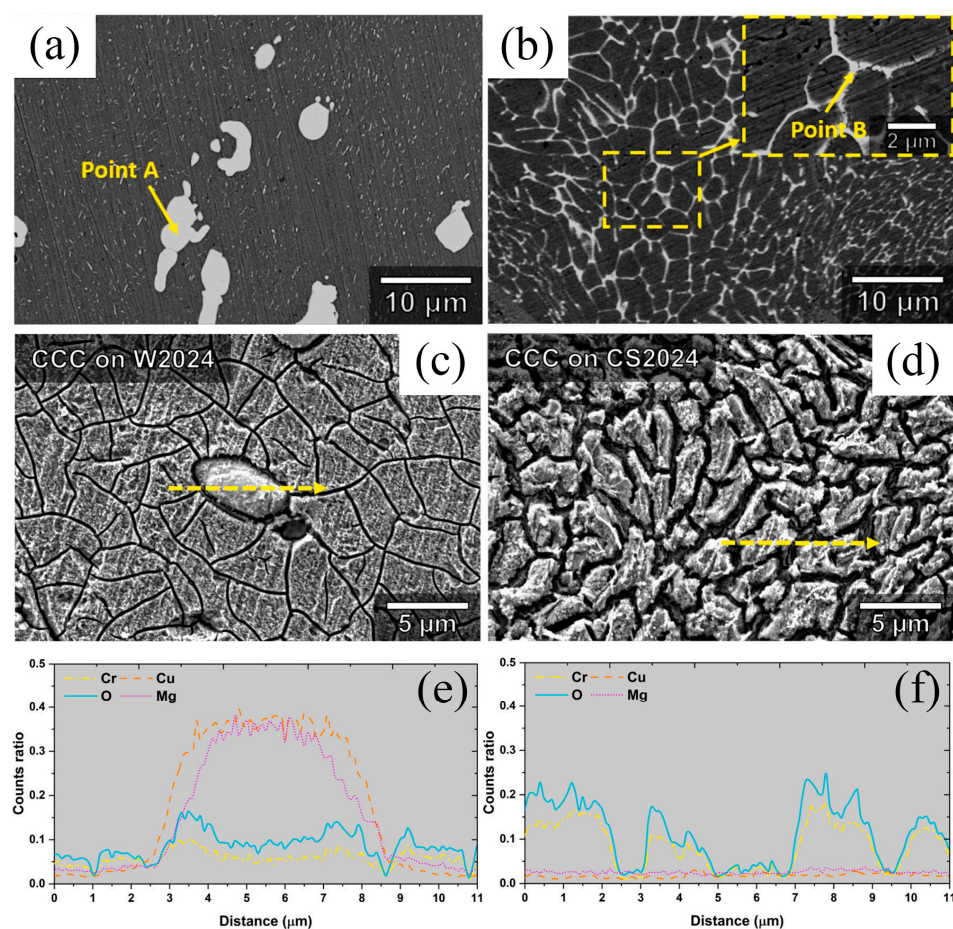


Figure 12. BSE images of the microstructures of W2024 (a) and CS2024 (b). SE images for the microstructure of CCC on W2024 (c) and CS2024 (d). For the EDS elemental line scan for CCC on W2024 (e) and CS2024 (f), yellow dot arrows in SE images indicate the path where the line scan analysis was conducted (adapted from reference [114], © Elsevier).

It can be discerned from Figure 13a that, in contrast to the bare CS2024, the polarization curve of CCC exhibits a passivation zone and pitting potential, with a marked reduction in I_{corr} . This indicates that CCC effectively inhibits the anodic reaction kinetics and improves corrosion resistance. Figure 13b also reflects the inhibitory effect of CCC on the cathodic reaction kinetics. The sharp increase in I_{corr} at the pitting potential implies the emergence of damage on the CCC. In the later stage of the polarization test, the separation of CCC from the substrate causes the polarization curve to almost overlap with that of the bare CS2024 [114]. Although the CCC on CS2024 possesses more defects (Figure 12d), the polarization curve reveals similar corrosion resistance for both CCCs. This might be associated

with the self-repairing mechanism of the chromate conversion coating [115], and the dissimilar stability of the corrosion behaviors of the two can account for the differences in the curves. In the subsequent immersion corrosion test, the corrosion resistance of the CCCs on both did not exhibit substantial differences within 48 h. However, when the time exceeded 48 h, the corrosion resistance of the CCC on CS2024 deteriorated rapidly compared to that on W2024. Kim et al. [114] offered a rational explanation: CCC's structural morphology leads to a distinctive corrosion propagation behavior in the later immersion stage.

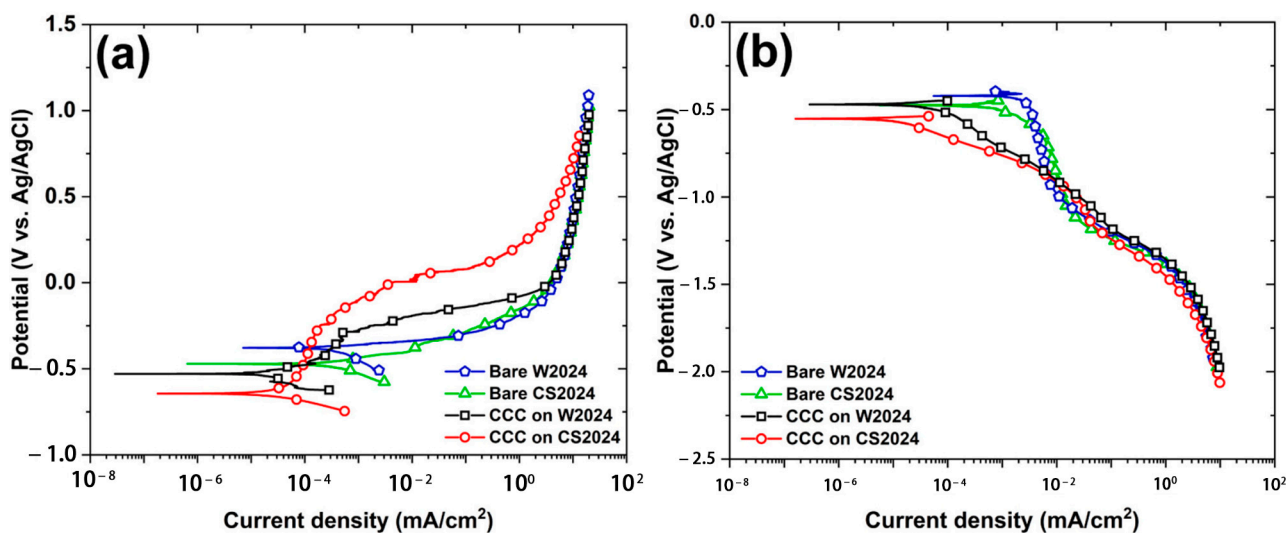


Figure 13. Potentiodynamic tests for bare and CCC of W2024 and CS2024 in 0.1 M Na₂SO₄ + 0.005 M NaCl solution at room temperature after 2 h OCP measurement: (a) anodic and (b) cathodic polarization (adapted from reference [114], © Elsevier).

6. Electrochemical Processing

6.1. Anodic Oxidation

Anodic oxidation (AO) is an electrochemical technology with extensive applications. It operates at a voltage lower than the breakdown voltage of oxides and is commonly employed to form thick and stable oxide films on valve metals like Mg, Al, Ti, Nb, and their alloys [111]. Nevertheless, a sole AO process is challenging in directly offering satisfactory corrosion and wear protection for the substrates [116]. The prominent structural feature of CS coatings is surface roughness and porosity, typically undesired in structural materials. However, based on this, AO has instilled new vigor into developing CS technology in functional material domains such as biology and electronics. The research related to the AO post-treatment of CS coatings has been listed in Table 7.

It is widely acknowledged that titanium and its alloys have been extensively utilized in the biomedical domain due to their superior biocompatibility. Particularly for osteoblasts, the porous TiO₂ layer on the titanium surface offers an optimal environment for their growth and proliferation, facilitating a robust chemical bond between the implant and the surrounding bone tissue [117]. Vilardell et al. [118] investigated the feasibility of applying CS CP-Ti coating in conjunction with AO post-treatment to joint prostheses. Severely deformed Ti particles constitute the coating's rough and porous surface morphology (Figure 14a), and the subsequent AO forms a TiO₂ nanotube layer on the coating surface (Figure 14b). The cracks on the oxide film can be ascribed to the stress concentration generated during the AO process or the corrosion effect of the electrolyte on the interface of weakly bonded particles [119]. In the *in vitro* osteoblast cultivation experiment, the high hydrophilicity of the nanoporous structure of the oxide layer enhanced cell adhesion, significantly augmenting the cell proliferation value (Figure 14c,d). Currently, the

Vilardell team [120] has affirmed that the highly rough CS CP-Ti coating complies with the requirements of the ASTM standard specification for joint prostheses. In contrast to the commonly employed Ti coating preparation process for joint prostheses in commercial settings, namely, vacuum plasma spraying (VPS), CS can be conducted under normal pressure, featuring higher operational flexibility and economic benefits.

Table 7. Summary of anodic oxidation on CS coatings.

References	Coatings	Anodic Oxidation Parameters		Findings
		Electrolyte Composition	Electrical Parameters	
[118,120]	Ti	5 wt% H ₂ O 0.5 wt% NH ₄ F 94.5 wt% (CH ₂ OH) ₂	Voltage: 30 V Span: 45 min	AO can significantly improve the hydrophilicity of CS coating and then promote cell proliferation and differentiation, mainly due to the TiO ₂ nanotube structure formed on the coating's surface.
[119]	Al	10 wt% H ₂ SO ₄ 90 wt% H ₂ O	Anode current density: 2 A/dm ² Span: 40 min	The dense alumina film formed by anodizing effectively improves the coating's corrosion and wear resistance. When the coating's porosity exceeds 1.5%, its corrosion resistance after anodizing is significantly reduced. This is attributed to the difficulty forming a dense oxide layer due to the electrolyte's infiltration.
[121]	Al	Sulfuric acid solution	Voltage: 13~22 V Current density: 1~2 A/dm ² Span: 30 min	The optimum anodizing process for the coating surface is 10% sulfuric acid concentration, 25 V voltage, and 60 min oxidation time, at which time the highest hardness and wear resistance can be obtained.
[122]	Al/Al ₂ O ₃	0~10 vol.% H ₂ SO ₄	Voltage: 0~30 V Span: 0~90 min	The nanoporous SnO films obtained by cold spraying Sn coating after AO and water-assisted heat treatment have good capacitance characteristics. They can be used as potential electrode materials for energy storage applications.
[123,124]	Sn	[H ₂ C ₂ O ₄] = 0.3 mol/L	Voltage: 6 V Span: 10 min	The introduction of graphene improves the density and bonding strength of the coating while exerting high strength and lubrication anti-wear properties. The hardness and wear resistance of the AO layer are also significantly improved.
[125]	7075Al/Al ₂ O ₃ //G/7075Al/Al ₂ O ₃	70 wt% 0.3 mol/L H ₂ C ₂ O ₄ 30 wt% C ₂ H ₅ OH	Voltage: 60 V Span: 30 min	

Zarei et al. [123] were the pioneers who reported the fabrication of nanoporous SnO films on CS Sn coatings using AO technology. The research revealed that the oxide films produced by a sole AO process exhibited a relatively dense surface, with most of the pores being closed, thereby incapacitating their porous nature. Hence, they incorporated pulsed ultrasonic waves during the AO process. With the aid of ultrasonic waves, oxygen was facilitated to escape smoothly from the pores in the final stage of oxide growth, preventing the continuous accumulation of oxygen from causing channel blockage [123], thereby successfully attaining a uniform open porous structure. Furthermore, owing to the disparity in surface structure between the Sn coating and the Sn foil, the oxide film on the Sn coating possessed smaller pore diameters. On this foundation, the Zarei team [124] also conducted water-assisted annealing treatment on the nanoporous SnO films on the Sn coating. Through a dissolution-precipitation mechanism, crystalline SnO₂ was formed on the inner surface of the nanotubes, which augmented the active surface area of the film. This enabled the Sn electrode to exhibit favorable capacitive properties at low current densities. Nevertheless, at high current densities, the insufficiency of active sites resulted in a decline in specific capacitance [124], which awaits further optimization. In contrast to the direct preparation of porous oxide films on Sn foils, CS offers more choices for substrate

materials. The CS + AO composite process holds promise for application in the future fabrication of electrode materials in the energy storage field.

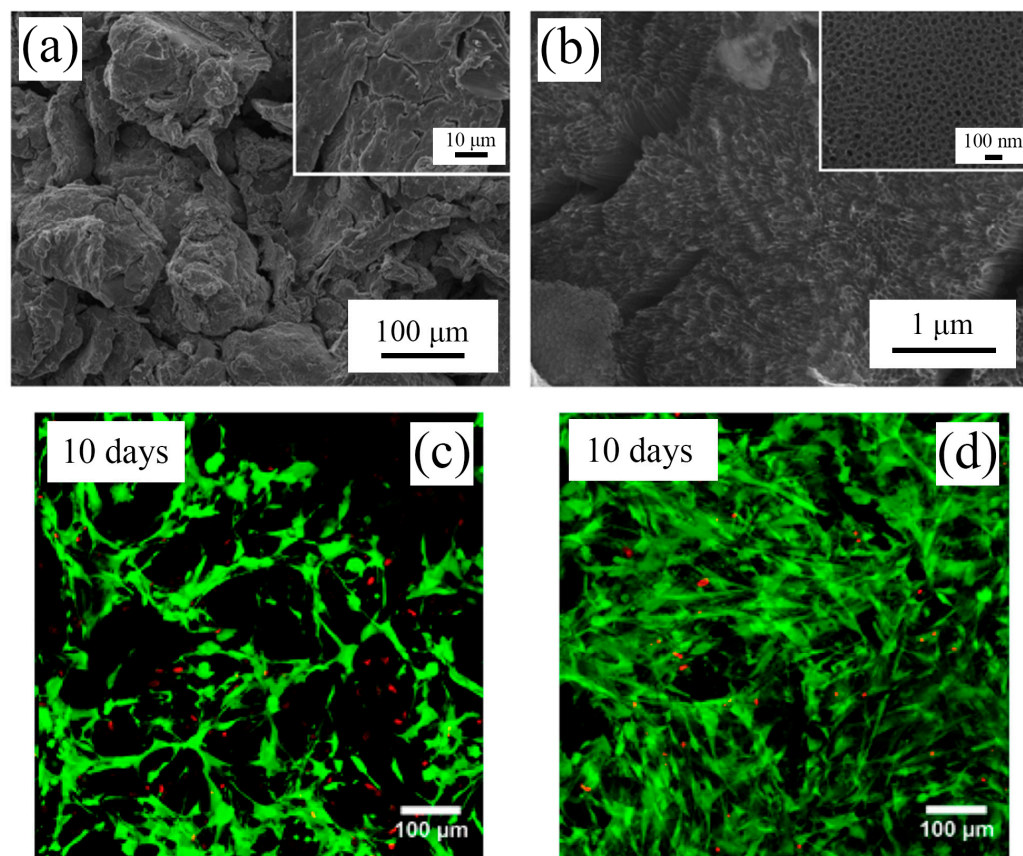


Figure 14. FESEM micrographs of the (a) cross-section and (b) the anodic oxidation treatments onto CS CP-Ti coating. Live/Dead assay at 10 days of hOB culture onto (c) as-sprayed CS CP-Ti coating and after (d) anodic oxidation (adapted from reference [118], © Elsevier).

6.2. Plasma Electrolytic Oxidation

Plasma electrolytic oxidation (PEO), also referred to as micro-arc oxidation (MAO), constitutes a plasma-assisted electrochemical technique for generating protective oxide coatings on lightweight metals like aluminum alloys [126,127] and is frequently employed to enhance the corrosion resistance and wear resistance of metallic materials. Nevertheless, the sole PEO process is restricted to valve metals such as Al, Mg, and Ti [128], remaining ineffective for most other metals. Fortunately, the PEO process has evolved into the CS + PEO combined process, affording opportunities for the corrosion and wear protection of the surfaces of more metallic materials. The research regarding the PEO post-treatment of CS coatings has been listed in Table 8.

The PEO process simultaneously encompasses electrochemical, thermochemical, and plasma phase reactions. Its film formation mechanism is highly complex, mainly encompassing four stages: anodic oxidation, spark discharge, micro-arc oxidation, and arc discharge [128–130]. When the applied voltage exceeds the breakdown value of the oxide, the high-energy plasma instantaneously melts the substrate and the oxide. The molten oxide enters the electrolyte through the discharge channel, solidifies, and deposits, forming a PEO coating [111]. Currently, the CS + PEO composite process primarily focuses on Al or Al-based composite materials. The microstructure morphology of the CS coating after PEO treatment is depicted in Figure 15. It can be observed that the PEO coating consists of an external loose layer and an internal dense layer. The loose sponge-like morphology is a typical

characteristic of oxide growth in a soft spark state [131], while the spherical micropores are high-pressure discharge channels formed by gas escape when the oxide melts [132]. There are disconnected microcracks in the oxide layer, which are attributed to the thermal stress resulting from the rapid cooling of the molten oxide [133]. The PEO coating is transformed by consuming the substrate material, with uniform coating thickness and a smooth growth interface, typically exhibiting excellent interfacial adhesion. Although the presence of pores usually deteriorates the performance of CS coatings, studies have indicated [128] that these pores can facilitate the growth of PEO coatings. After incorporating a certain proportion of Al_2O_3 into pure Al (Figure 15b), the intense compaction effect [134] enhances the density of the coating. Therefore, a thicker oxide layer is formed on the pure Al coating (Figure 15a) under the same PEO conditions.

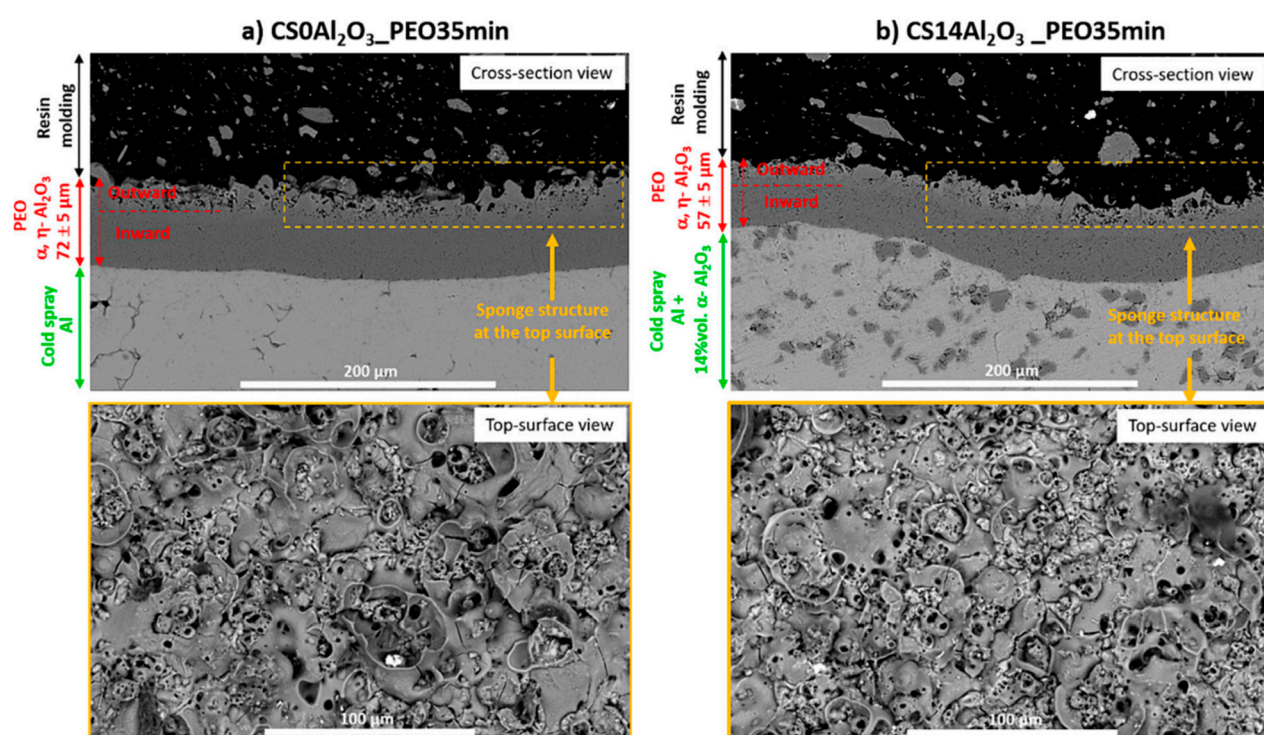


Figure 15. Cross-section and top-surface SEM micrographs were recorded in BSE imaging mode on the following samples: (a) CS0Al₂O₃_PEO35min and (b) CS14Al₂O₃_PEO35min (adapted from reference [131], © Elsevier).

Table 8. Summary of plasma electrolytic oxidation on CS coatings.

References	Coatings	PEO Parameters		Findings
		Electrolyte Composition	Electrical Parameter	
[128]	Al	[Na ₂ SiO ₃] = 1.65 g/L [KOH] = 1 g/L	Frequency: 100 Hz Anode current density: 48 A/dm ² Q _p /Q _n = 0.9 Span: 8–35 min	Compared with the single-phase PEO process of blocks, the growth kinetics of the biphasic CS + PEO oxide layer is three times higher, mainly due to the higher porosity of the CS coating. PEO coating is mainly composed of α -Al ₂ O ₃ and γ -Al ₂ O ₃ , accompanied by a small amount of Al, and its corrosion resistance is higher than that of Al coating. After PEO, the wear resistance of Al coating is greatly improved due to the formation of a high-hardness and dense oxide layer.
[135]	Al	[Na ₂ SiO ₃] = 9 g/L [NaOH] = 5 g/L [NaF] = 0.5 g/L [SiO ₂] = 3 g/L	Voltage: 450 V Span: 20 min	
[136]	Al	[NaAlO ₂] = 7.5 g/L [KOH] = 1 g/L [Na ₃ PO ₄] = 2.5 g/L	Voltage: 500 V Frequency: 500 Hz Duty cycle: 40% Span: 5 min	

Table 8. Cont.

References	Coatings	PEO Parameters		Findings
		Electrolyte Composition	Electrical Parameter	
[131]	Al// Al/ α -Al ₂ O ₃	[Na ₂ SiO ₃] = 1.65 g/L [KOH] = 1 g/L	Frequency: 100 Hz Anode current density: 66 A/dm ² Cathode current density: 39 A/dm ² Q _p /Q _n = 0.9 Span: 20–35 min	In the PEO process, α -Al ₂ O ₃ particles are crushed and melted by the arc and uniformly dispersed in the oxide layer, improving the coating's wear resistance.
[133]	Al// Al/ α -Al ₂ O ₃	[NaAlO ₂] = 0.18 mol/L [KOH] = 0.035 mol/L	Voltage: 400 V Frequency: 500 Hz Duty cycle: 60% Span: 20 min	PEO significantly improves the corrosion resistance and wear resistance of Al coating, and the addition of α -Al ₂ O ₃ can enhance the improvement effect.
[137]	Al/ α -Al ₂ O ₃	[Na ₂ SiO ₃] = 5 g/L [KOH] = 1 g/L	Anode current density: 30 A/dm ² Cathode current density: 33.33 A/dm ² Q _p /Q _n = 0.9 and ∞ Span: 22 min	The oxidation layer grows faster in soft spark mode than in unipolar mode; the higher α -Al ₂ O ₃ content and dense oxide layer structure improves wear resistance.
[138]	Al// Al/CNT	[NaAlO ₂] = 8 g/L [KOH] = 1 g/L [EDTA-2Na] = 2 g/L [Na ₃ C ₆ H ₅ O ₇ ·2H ₂ O] = 2 g/L	Frequency: 2000 Hz Positive current: 0.6 A Negative current: 0.3 A Duty cycle: 20% Span: 10 min	The wear resistance of the composite coating is greatly improved after PEO, thanks to the hard oxide layer and the strengthening and self-lubrication of carbon elements.
[139]	7075Al	[NaAlO ₂] = 8 g/L [KOH] = 1 g/L [EDTA-2Na] = 2 g/L [Na ₃ C ₆ H ₅ O ₇ ·2H ₂ O] = 2 g/L	Frequency: 2000 Hz Positive current: 0.5 A Negative current: 0.3 A Duty cycle: 20% Span: 10 min	The PEO oxide layer is dominated by γ -Al ₂ O ₃ , accompanied by a small amount of α -Al ₂ O ₃ , and the hardness is as high as 1353 HV _{0.01} . The corrosion and wear resistance of the Al7075 coating are greatly improved.
[140]	Zr/Al	[Na ₂ SiO ₃] = 1.65 g/L [KOH] = 1 g/L	Frequency: 100 Hz Anode current density: 65 A/dm ² Q _p /Q _n = 0.9 Span: 20 min	The feasibility of preparing a ZrO ₂ /Al ₂ O ₃ composite coating on a cold-sprayed Zr/Al coating surface by PEO is demonstrated.
[141]	Ti	[Na ₂ SiO ₃] = 30 g/L	Voltage: 380 V Frequency: 400 Hz Duty cycle: 10% Span: 7 min	The rough and porous structure of Ti-PEO coating results in poor mechanical properties and wear resistance, but the more stable chemical properties of the oxide may improve corrosion resistance.

Based on the high insulation and chemical stability of metal oxides, PEO post-treatment can effectively enhance the corrosion protection performance of CS coatings. As can be observed from Figure 16a, the corrosion potential of the Al coating undergoes a positive shift after PEO treatment; its corrosion current density is the lowest among the three, suggesting the best corrosion resistance. Owing to the rather complex structure of the Al₂O₃ coating formed by PEO, apart from the stable α phase, metastable β and γ phases are typically present [142]. Consequently, the addition of α -Al₂O₃ can further enhance the corrosion resistance of the PEO coating (Figure 16b). Nevertheless, as PEO coatings generally possess a high porosity (up to 10–20%) [143,144], and most of the pores are connected to the surface. This provides a channel for the contact of the corrosive liquid with the substrate. Hence, it is indispensable to conduct post-treatment on the PEO coating. Considering that the oxide layer typically has a significantly higher hardness and melting point than the base material, the aforementioned methods, such as SP and HT, are no longer applicable. In this regard, Rao et al. [145] employed an organic sealing agent to treat the PEO coating of CS 7075Al. They discovered that the I_{corr} of the PEO coating decreased by an order of magnitude after sealing. Even after 7 days of pre-immersion, the corrosion rate could remain very low. However, corrosion occurrence still cannot be precluded due to

the difficulty in filling the micropores and microcracks within the coating with the sealing agent [145]. In summary, for the CS-PEO coatings to achieve a more desirable corrosion protection effect, higher demands are imposed on the PEO process and sealing treatment, which awaits further optimization exploration.

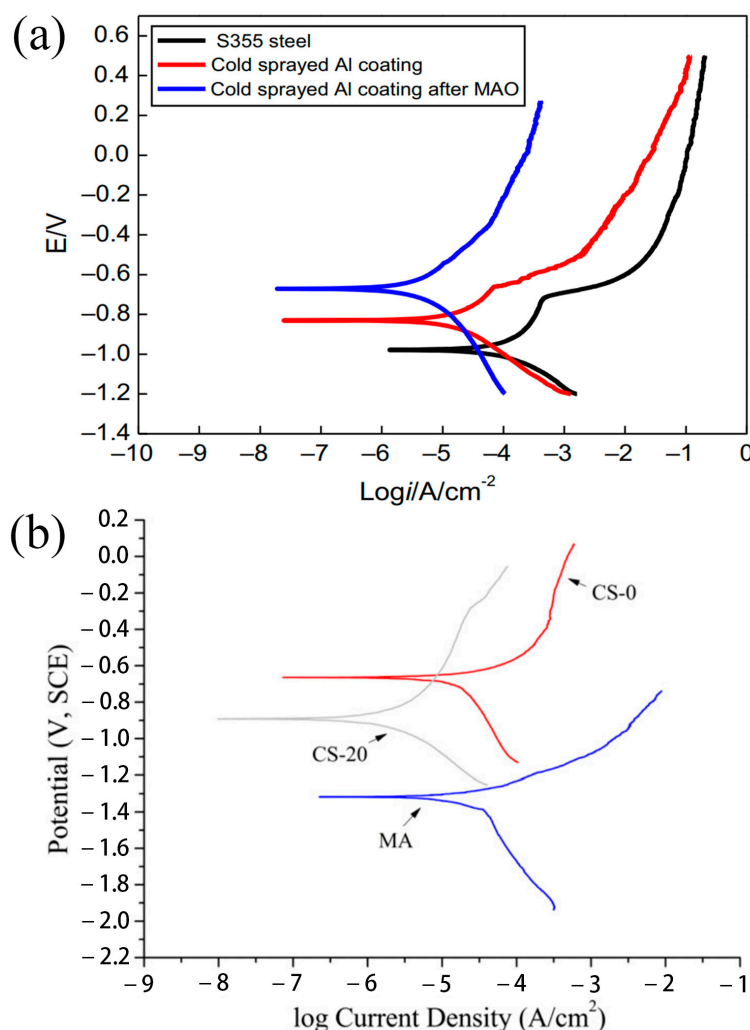


Figure 16. (a) Polarization curves of S355 steel, cold sprayed Al, and MAO coating (adapted from reference [135], © Emerald Group). (b) Polarization curves of AZ91D(MA), cold-sprayed Al coating (CS-0), and cold-sprayed Al/Al₂O₃ composite coating (CS-20) in 3.5% sodium chloride solution (adapted from reference [133], © Elsevier).

Although the pores in PEO coatings are disadvantageous to their corrosion protection performance, a certain porosity can endow the coating with lower stiffness. Combined with the excellent adhesion between the oxide layer and the substrate, the CS + PEO coatings demonstrate outstanding wear resistance, which is unparalleled by other post-treatment methods. For example, nickel aluminum bronze (NAB), which is extensively utilized in manufacturing wear-resistant components, such as bearings and bushings, witnessed its sliding wear resistance increase by more than nine times after Yürektürk [136] covered the surface of NAB alloy with an Al-Al₂O₃ two-phase coating using CS + PEO. This was primarily attributed to the oxide layer's high hardness and strong anti-spalling properties [130,133], followed by the lubricating effect of the α -Al₂O₃ phase [131]. Zhang et al. [138] discovered that introducing carbon could reduce the wear rate of PEO coatings by an order of magnitude and exhibited excellent anti-friction characteristics, ascribed to the enhancement of coating hardness and the self-lubricating effect of carbon. Additionally,

sealing treatment [145] can marginally improve the wear resistance of PEO coatings. Notably, PEO coatings typically possess a relatively high surface roughness, which can cause severe wear to the mating workpieces. Moreover, under wear conditions with impact loads, the hard and brittle nature of the oxide layer also brings the risk of fracture failure. There is still a scarcity of optimization efforts regarding the wear resistance of CS + PEO coatings, which merits more attention.

7. Conclusions and Outlook

Currently, the research on CS coatings has progressed from experimental and theoretical investigations to large-scale industrial production, and higher demands have been placed on the performance of CS coatings. Despite a considerable amount of research efforts in the parameter optimization of CS, the inherent bonding mode among particles still results in the various properties of the coatings being less than satisfactory. Fortunately, remarkable advancements have been achieved in the post-treatment techniques of CS coatings. This paper elaborately discusses and summarizes the influences of eight post-treatment methods on the microstructure and various properties of CS coatings (Table 9) to better comprehend the significance of post-treatment for developing CS technology.

Table 9. Improvements in eight post-treatment processes and their effects on various properties of CS coatings.

Post-Processing Technology	Strengthening Mechanism	Refinement and Dispersion of Ceramic Reinforcement Particles	Reduce Porosity	Plasticity	Hardness	Ultimate Tensile Strength	Bond Strength	Wear Resistance	Corrosion Resistance
HT	Thermal	×	✓	1	2	1	1	1	1
LR	Thermal	×	✓	0	1	0	1	1	1
FSP	Thermo-mechanical coupling	✓	✓	1	1	1	1	1	1
SP	Mechanical	×	✓	2	1	2	0	1	1
HR	Thermo-mechanical coupling	✓	✓	1	1	1	1	1	1
CCC	Chemical conversion	×	×	2	0	2	2	0	1
AO	Electrochemical conversion	×	×	2	1	2	2	1	1
PEO	Electrochemical conversion	×	×	2	1	2	2	1	1

Notes: (✓): Feasible, (×): Not feasible, (0): No research, (1): Obvious improvement, (2): No improvement/decrease.

HT is extensively employed due to its significant effect and straightforward operation. The elimination or reduction of defects is achieved through the solid-state sintering of CS coatings. However, its optimization effect on porous and loose coatings is limited, and the potential adverse impacts that high temperatures might bring to the substrate must be considered. LR has a negligible thermal influence on the substrate and can accomplish complete densification of the remelted zone by melting the material. Nevertheless, large pores are prone to form at the interface of the remelted zone. FSP is particularly applicable for the post-treatment of ceramic-reinforced CS composite coatings because of its intense stirring effect. Nevertheless, the high hardness of the coatings will impose substantial difficulties on the processing; SP can markedly reduce the porosity of CS coatings. However, it is challenging to introduce the desired beneficial residual compressive stress, and the coating surface is prone to damage during the SP process, forming new cracks. HR is primarily directed toward CS composite plates. It can significantly ameliorate the size and distribution of reinforcing particles in the composite coating and simultaneously enhance the bonding strength between the coating and the substrate. Combining CS and HR with

HT can further improve comprehensive performance. CS + HR is anticipated to be an economical and reliable novel process for fabricating metal composite plates. Research on CCC based on CS coatings remains in the exploratory phase. Chromate conversion coatings were once commercially utilized and could effectively enhance the corrosion resistance of CS aluminum alloy coatings. However, due to the highly carcinogenic nature of hexavalent chromium, which causes significant harm to both human beings and the environment, international organizations have prohibited it. Further exploration could be carried out on the effects of phosphate, manganese, rare-earth-based, and composite conversion coatings on CS coatings. The loose and porous character of the AO layer on the CS coating leads to relatively poor corrosion and wear resistance. Still, certain research advancements have been achieved in functional materials. By contrast, when combined with further post-treatment, the PEO coating can offer robust dual protection against corrosion and wear for the substrate. Nevertheless, when being applied, the consumption of relatively costly electrical equipment and energy needs to be considered.

The post-treatment technologies for CS coatings are continuously evolving and innovating. However, despite significant research efforts conducted in this field, current advancements remain insufficient to facilitate the widespread commercialization of CS coatings, with several potential research directions requiring further investigation as outlined below:

- (1) The enhancement effects of post-treatment technologies on the microstructure and properties of CS coatings are influenced not only by post-treatment parameters but also by the intrinsic characteristics of coating materials and CS processing conditions, with these factors exhibiting interconnected and complex interdependencies. However, systematic investigations into their synergistic mechanisms remain scarce, and consensus regarding optimal process parameters for most materials has yet to be established, which should be prioritized in future research endeavors to address current technological limitations.
- (2) The incorporation of ceramic reinforcement particles demonstrates significant potential for enhancing the wear resistance, mechanical properties, and multifunctional performance of CS coatings. However, due to the relatively low temperatures inherent to the deposition process, ceramic particles exhibit limited plastic deformation capacity, with interfacial interactions between metallic and ceramic constituents being predominantly governed by mechanical bonding mechanisms, thus resulting in composite coatings characterized by inadequate interfacial adhesion and susceptibility to brittle fracture. Consequently, such hybrid systems require post-treatment interventions to optimize interfacial bonding strength and fully exploit the reinforcement potential of ceramic particulates. Although current research in this domain remains limited, systematic investigations into bonding mechanisms and the development of advanced post-processing methodologies using integrated experimental and numerical simulation approaches represent critical imperatives for technological advancement.
- (3) Current post-treatment technologies predominantly remain at experimental research stages with inherent limitations, demonstrating restricted optimization efficacy primarily targeting one or two specific properties under particular operational conditions while failing to achieve substantial comprehensive performance enhancement of CS coatings using singular processing methods. Future developments should prioritize the strategic integration of multiple post-treatment approaches, such as hybrid techniques exemplified by HT + SP and LR + SP + PEO composite technologies, to leverage complementary advantages that collectively address the comprehensive performance requirements of CS coatings under diverse complex service conditions.

Author Contributions: Conceptualization, Q.W. and Y.H.; methodology, Q.W. and Y.H.; software, Q.W. and C.S.R.; validation, Q.W., Y.H., J.L. and H.L.; formal analysis, Q.W. and C.S.R.; investigation, Y.H.; resources, Z.W.; data curation, Q.W. and Y.H.; writing—original draft preparation, Y.H. and C.S.R.; writing—review and editing, C.S.R., Q.W. and Y.H.; visualization, Y.H.; supervision, Q.W.; project administration, Q.W.; funding acquisition, Q.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Natural Science Foundation of Hunan Province, China (2023JJ30153).

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

References

1. Papyrin, A.; Kosarev, V.; Klinkov, S.; Alkimov, A.; Fomin, V. Cold spray technology. *Adv. Mater. Process.* **2001**, *159*, 49–51.
2. Yin, S.; Cavaliere, P.; Aldwell, B.; Jenkins, R.; Liao, H.; Li, W.; Lupoi, R. Cold spray additive manufacturing and repair: Fundamentals and applications. *Addit. Manuf.* **2018**, *21*, 628–650. [\[CrossRef\]](#)
3. Cadney, S.; Brochu, M.; Richer, P.; Jodoin, B. Cold gas dynamic spraying as a method for freeforming and joining materials. *Surf. Coat. Technol.* **2008**, *202*, 2801–2806. [\[CrossRef\]](#)
4. Assadi, H.; Kreye, H.; Gärtner, F.; Klassen, T. Cold spraying—A materials perspective. *Acta Mater.* **2016**, *116*, 382–407. [\[CrossRef\]](#)
5. Rokni, M.; Nutt, S.; Widener, C.; Champagne, V.; Hrabe, R. Review of Relationship Between Particle Deformation, Coating Microstructure, and Properties in High-Pressure Cold Spray. *J. Therm. Spray Technol.* **2017**, *26*, 1308–1355. [\[CrossRef\]](#)
6. Ajdelsztajn, L.; Schoenung, J.; Jodoin, B.; Kim, G. Cold spray deposition of nanocrystalline aluminum alloys. *Metall. Mater. Trans. A* **2005**, *36*, 657–666. [\[CrossRef\]](#)
7. Li, C.; Li, W.; Wang, Y. Formation of metastable phases in cold-sprayed soft metallic deposit. *Surf. Coat. Technol.* **2005**, *198*, 469–473. [\[CrossRef\]](#)
8. Suo, X.; Guo, X.; Li, W.; Planche, M.P.; Bolot, R.; Liao, H.; Coddet, C. Preparation and characterization of magnesium coating deposited by cold spraying. *J. Mater. Process. Technol.* **2012**, *212*, 100–105. [\[CrossRef\]](#)
9. Spencer, K.; Fabijanic, D.; Zhang, M. The use of Al–Al₂O₃ cold spray coatings to improve the surface properties of magnesium alloys. *Surf. Coat. Technol.* **2009**, *204*, 336–344. [\[CrossRef\]](#)
10. Gardon, M.; Latorre, A.; Torrell, M.; Dosta, S.; Guilemany, J.M. Cold Gas Spray Titanium coatings onto a biocompatible polymer. *Mater. Lett.* **2013**, *106*, 97–99. [\[CrossRef\]](#)
11. Sun, W.; Tan, A.W.; Wu, K.; Yin, S.; Yang, X.; Marinescu, I.; Liu, E. Post-Process Treatments on Supersonic Cold Sprayed Coatings: A Review. *Coatings* **2020**, *10*, 123. [\[CrossRef\]](#)
12. Li, W.; Cao, C.; Yin, S. Solid-state cold spraying of Ti and its alloys: A literature review. *Prog. Mater. Sci.* **2020**, *110*, 100633. [\[CrossRef\]](#)
13. Wang, H.; Li, P.; Guo, W.; Ma, G.; Wang, H. Copper-Based Composite Coatings by Solid-State Cold Spray Deposition: A Review. *Coatings* **2023**, *13*, 479. [\[CrossRef\]](#)
14. Siddique, S.; Bernussi, A.A.; Husain, S.W.; Yasir, M. Enhancing structural integrity, corrosion resistance and wear properties of Mg alloy by heat treated cold sprayed Al coating. *Surf. Coat. Technol.* **2020**, *394*, 1258–1282. [\[CrossRef\]](#)
15. Sun, W.; Bhowmik, A.; Tan, A.W.-Y.; Li, R.; Xue, F.; Marinescu, I.; Liu, E. Improving microstructural and mechanical characteristics of cold-sprayed Inconel 718 deposits via local induction heat treatment. *J. Alloys Compd.* **2019**, *797*, 1268–1279. [\[CrossRef\]](#)
16. Chavan, N.M.; Ramakrishna, M.; Phani, P.S.; Rao, D.S.; Sundararajan, G. The influence of process parameters and heat treatment on the properties of cold sprayed silver coatings. *Surf. Coat. Technol.* **2011**, *205*, 4798–4807. [\[CrossRef\]](#)
17. Phani, P.S.; Rao, D.S.; Joshi, S.V.; Sundararajan, G. Effect of Process Parameters and Heat Treatments on Properties of Cold Sprayed Copper Coatings. *J. Therm. Spray Technol.* **2007**, *16*, 425–434. [\[CrossRef\]](#)
18. Yang, K.; Li, W.; Yang, X.; Xu, Y.; Vairis, A. Effect of heat treatment on the inherent anisotropy of cold sprayed copper deposits. *Surf. Coat. Technol.* **2018**, *350*, 519–530. [\[CrossRef\]](#)
19. Li, W.Y.; Guo, X.P.; Verdy, C.; Dembinski, L.; Liao, H.L.; Coddet, C. Improvement of microstructure and property of cold-sprayed Cu–4 at.%Cr–2 at.%Nb alloy by heat treatment. *Scr. Mater.* **2006**, *55*, 327–330. [\[CrossRef\]](#)
20. Spencer, K.; Zhang, M.X. Heat treatment of cold spray coatings to form protective intermetallic layers. *Scr. Mater.* **2009**, *61*, 44–47. [\[CrossRef\]](#)
21. Huang, R.; Sone, M.; Ma, W.; Fukanuma, H. The effects of heat treatment on the mechanical properties of cold-sprayed coatings. *Surf. Coat. Technol.* **2015**, *261*, 278–288. [\[CrossRef\]](#)
22. Judas, J.; Zapletal, J.; Řehořek, L.; Jan, V. Effects of annealing temperature on microstructure and mechanical properties of cold sprayed AA7075. *Procedia Struct. Integr.* **2023**, *43*, 160–165. [\[CrossRef\]](#)

23. Rokni, M.R.; Widener, C.A.; Ozdemir, O.C.; Crawford, G.A. Microstructure and mechanical properties of cold sprayed 6061 Al in As-sprayed and heat treated condition. *Surf. Coat. Technol.* **2016**, *309*, 641–650. [\[CrossRef\]](#)
24. Wu, D.; Li, W.; Yang, X.; Zou, Y.; Su, Y.; Xu, Y. Heat Treatment Effects on the Microstructure, Mechanical and Wear Properties of an Al 2024 Cold Spray Additive Manufactured Deposit. *J. Therm. Spray Technol.* **2023**, *32*, 2378–2393. [\[CrossRef\]](#)
25. Murray, J.W.; Zuccoli, M.V.; Hussain, T. Heat Treatment of Cold-Sprayed C355 Al for Repair: Microstructure and Mechanical Properties. *J. Therm. Spray Technol.* **2018**, *27*, 159–168. [\[CrossRef\]](#)
26. Li, W.-Y.; Yang, C.; Liao, H. Effect of vacuum heat treatment on microstructure and microhardness of cold-sprayed TiN particle-reinforced Al alloy-based composites. *Mater. Des.* **2011**, *32*, 388–394. [\[CrossRef\]](#)
27. Lee, H.Y.; Jung, S.H.; Lee, S.Y.; Ko, K.H. Fabrication of cold sprayed Al-intermetallic compounds coatings by post annealing. *Mater. Sci. Eng. A* **2006**, *433*, 139–143. [\[CrossRef\]](#)
28. Chavan, N.M.; Kiran, B.; Jyothirmayi, A.; Phani, P.S.; Sundararajan, G. The Corrosion Behavior of Cold Sprayed Zinc Coatings on Mild Steel Substrate. *J. Therm. Spray Technol.* **2013**, *22*, 463–470. [\[CrossRef\]](#)
29. Ren, Y.Q.; King, P.C.; Yang, Y.S.; Xiao, T.Q.; Chu, C.; Gulizia, S.; Murphy, A.B. Characterization of heat treatment-induced pore structure changes in cold-sprayed titanium. *Mater. Charact.* **2017**, *132*, 69–75. [\[CrossRef\]](#)
30. Baiamonte, L.; Pulci, G.; Gisario, A.; Paglia, L.; Marino, A.L.; Tului, M.; Marra, F. WC-Ti Coatings Deposited Via Cold Gas Spray and Modified by Laser and Furnace Heat Treatments. *J. Therm. Spray Technol.* **2021**, *30*, 2083–2098. [\[CrossRef\]](#)
31. Lett, S.; Cormier, J.; Quet, A.; Villechaise, P.; Meillot, E.; Hémery, S. Microstructure optimization of cold sprayed Ti-6Al-4V using post-process heat treatment for improved mechanical properties. *Addit. Manuf.* **2024**, *86*, 104168. [\[CrossRef\]](#)
32. Kumar, S.; Jyothirmayi, A.; Wasekar, N.; Joshi, S.V. Influence of annealing on mechanical and electrochemical properties of cold sprayed niobium coatings. *Surf. Coat. Technol.* **2016**, *296*, 124–135. [\[CrossRef\]](#)
33. Koivuluoto, H.; Vuoristo, P. Structural Analysis of Cold-Sprayed Nickel-Based Metallic and Metallic-Ceramic Coatings. *J. Therm. Spray Technol.* **2010**, *19*, 975–989. [\[CrossRef\]](#)
34. Wu, K.; Aprilia, A.; Tan, S.C.; Zhou, W. Rapid post processing of cold sprayed Inconel 625 by induction heating. *Mater. Sci. Eng. A* **2023**, *872*, 1449–1455. [\[CrossRef\]](#)
35. Ma, W.; Xie, Y.; Chen, C.; Fukunuma, H.; Wang, J.; Ren, Z.; Huang, R. Microstructural and mechanical properties of high-performance Inconel 718 alloy by cold spraying. *J. Alloys Compd.* **2019**, *792*, 456–467. [\[CrossRef\]](#)
36. Wong, W.; Irissou, E.; Vo, P.; Sone, M.; Bernier, F. Cold Spray Forming of Inconel 718. *J. Therm. Spray Technol.* **2013**, *22*, 413–421. [\[CrossRef\]](#)
37. Yang, G.-J.; Wang, H.-T.; Li, C.-J.; Li, C.-X. Effect of annealing on the microstructure and erosion performance of cold-sprayed FeAl intermetallic coatings. *Surf. Coat. Technol.* **2011**, *205*, 5502–5509. [\[CrossRef\]](#)
38. Meng, X.M.; Zhang, J.B.; Han, W.; Zhao, J.; Liang, Y.L. Influence of annealing treatment on the microstructure and mechanical performance of cold sprayed 304 stainless steel coating. *Appl. Surf. Sci.* **2011**, *258*, 700–704. [\[CrossRef\]](#)
39. Sundararajan, G.; Phani, P.S.; Jyothirmayi, A.; Gundakaram, R.C. The influence of heat treatment on the microstructural, mechanical and corrosion behaviour of cold sprayed SS 316L coatings. *J. Mater. Sci.* **2009**, *44*, 2320–2326. [\[CrossRef\]](#)
40. Zhang, L.-W.; Lu, L.; Wang, L.; Ning, X.-J.; Wang, Q.-S.; Wang, R.-X. Microstructural Characteristics and Oxidation Behavior of Low-Pressure Cold-Sprayed CoNiCrAlY Coatings. *J. Therm. Spray Technol.* **2017**, *26*, 1565–1572. [\[CrossRef\]](#)
41. Yang, Y.; Aprilia, A.; Wu, K.; Tan, S.C.; Zhou, W. Post-Processing of Cold Sprayed CoNiCrAlY Coatings on Inconel 718 by Rapid Induction Heating. *Metals* **2022**, *12*, 396. [\[CrossRef\]](#)
42. Xie, X.; Chen, C.; Ma, Y.; Xie, Y.; Liao, H. Influence of annealing treatment on microstructure and magnetic properties of cold sprayed Ni-coated FeSiAl soft magnetic composite coating. *Surf. Coat. Technol.* **2019**, *374*, 476–484. [\[CrossRef\]](#)
43. Yin, S.; Cizek, J.; Yan, X.; Lupoi, R. Annealing strategies for enhancing mechanical properties of additively manufactured 316L stainless steel deposited by cold spray. *Surf. Coat. Technol.* **2019**, *370*, 353–361. [\[CrossRef\]](#)
44. Jing, Z.; Dejun, K. Effect of laser remelting on microstructure and immersion corrosion of cold-sprayed aluminum coating on S355 structural steel. *Opt. Laser Technol.* **2018**, *106*, 348–356.
45. Astarita, A.; Genna, S.; Leone, C.; Minutolo, F.M.C.; Rubino, F.; Squillace, A. Study of the laser remelting of a cold sprayed titanium layer. *Procedia Cirp* **2015**, *33*, 452–457. [\[CrossRef\]](#)
46. Rubino, F.; Astarita, A.; Carlone, P.; Genna, S.; Leone, C.; Memola Capece Minutolo, F.; Squillace, A. Selective Laser Post-Treatment on Titanium Cold Spray Coatings. *Mater. Manuf. Process.* **2016**, *31*, 1500–1506. [\[CrossRef\]](#)
47. Marrocco, T.; Hussain, T.; McCartney, D.G.; Shipway, P.H. Corrosion Performance of Laser Posttreated Cold Sprayed Titanium Coatings. *J. Therm. Spray Technol.* **2011**, *20*, 909–917. [\[CrossRef\]](#)
48. Chen, Z.; Sun, X.; Li, Z.; Shi, Y.; Liu, X. Tribological Behavior of Cold Sprayed Cu402F Coating after Laser Remelting. *Surf. Technol.* **2017**, *46*, 161–167. (In Chinese)
49. Chen, Z.; Sun, X.; Li, Z.; Shi, Y.; Song, W.; Shuai, G. Corrosion Resistance of Ni-Al Bronze Based Coatings Prepared by Laser Remelting and Cold Spraying. *Surf. Technol.* **2017**, *17*, 23–27. (In Chinese)

50. Astarita, A.; Rubino, F.; Carlone, P.; Ruggiero, A.; Leone, C.; Genna, S.; Merola, M.; Squillace, A. On the Improvement of AA2024 Wear Properties through the Deposition of a Cold-Sprayed Titanium Coating. *Metals* **2016**, *6*, 185. [\[CrossRef\]](#)
51. Khun, N.W.; Tan, A.W.Y.; Sun, W.; Liu, E. Effects of Nd:YAG Laser Surface Treatment on Tribological Properties of Cold-Sprayed Ti-6Al-4V Coatings Tested against 100Cr6 Steel under Dry Condition. *Tribol. Trans.* **2019**, *62*, 391–402. [\[CrossRef\]](#)
52. Shikalov, V.S.; Katanaeva, D.A.; Vidyuk, T.M.; Golyshev, A.A.; Kosarev, V.F.; Kornienko, E.E.; Malikov, A.G.; Atuchin, V.V. Microstructural Modification of Cold-Sprayed Ti-Cr₃C₂ Composite Coating by Laser Remelting. *J. Compos. Sci.* **2023**, *7*, 500. [\[CrossRef\]](#)
53. Jing, Z.; Dejun, K. Effect of Laser Remelting on Friction-Wear Behaviors of Cold Sprayed Al Coatings in 3.5% NaCl Solution. *Materials* **2018**, *11*, 283. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Kang, N.; Verdy, C.; Coddet, P.; Xie, Y.; Fu, Y.; Liao, H.; Coddet, C. Effects of laser remelting process on the microstructure, roughness and microhardness of in-situ cold sprayed hypoeutectic Al-Si coating. *Surf. Coat. Technol.* **2017**, *318*, 355–359. [\[CrossRef\]](#)
55. Poza, P.; Munez, C.J.; Garrido-Maneiro, M.A.; Vezzù, S.; Trentin, A. Mechanical properties of Inconel 625 cold-sprayed coatings after laser remelting. Depth sensing indentation analysis. *Surf. Coat. Technol.* **2014**, *243*, 51–57. [\[CrossRef\]](#)
56. Sova, A.; Grigoriev, S.; Okunkova, A.; Smurov, I. Cold spray deposition of 316L stainless steel coatings on aluminium surface with following laser post-treatment. *Surf. Coat. Technol.* **2013**, *235*, 283–289. [\[CrossRef\]](#)
57. Jandaghi, M.R.; Pouraliakbar, H.; Hong, S.I.; Pavese, M. Grain boundary transition associated intergranular failure analysis at TMAZ/SZ interface of dissimilar AA7475-AA2198 joints by friction stir welding. *Mater. Lett.* **2020**, *280*, 128557. [\[CrossRef\]](#)
58. Gangil, N.; Siddiquee, A.N.; Maheshwari, S. Aluminium based in-situ composite fabrication through friction stir processing: A review. *J. Alloys Compd.* **2017**, *715*, 91–104. [\[CrossRef\]](#)
59. Ma, Z.Y. Friction Stir Processing Technology: A Review. *Metall. Mater. Trans. A* **2008**, *39*, 642–658. [\[CrossRef\]](#)
60. Mishra, R.S.; Ma, Z.Y.; Charit, I. Friction stir processing: A novel technique for fabrication of surface composite. *Mater. Sci. Eng. A* **2003**, *341*, 307–310. [\[CrossRef\]](#)
61. Perard, T.; Sova, A.; Robe, H.; Robin, V.; Zedan, Y.; Bocher, P.; Feulvarch, E. Friction stir processing of austenitic stainless steel cold spray coating deposited on 304L stainless steel substrate: Feasibility study. *Int. J. Adv. Manuf. Technol.* **2021**, *115*, 2379–2393. [\[CrossRef\]](#)
62. Mishra, R.S.; Ma, Z.Y. Friction stir welding and processing. *Mater. Sci. Eng. R Rep.* **2005**, *50*, 1–78. [\[CrossRef\]](#)
63. Xu, Y.; Ge, J.; Ji, B.; Li, W. Mechanical alloying of cold-sprayed Ni-Nb-Si composite coating by friction stir processing: Improvement in microstructure and resistance against molten silicates corrosion. *Surf. Coat. Technol.* **2022**, *451*, 129051. [\[CrossRef\]](#)
64. Huang, C.; Li, W.; Feng, Y.; Xie, Y.; Planche, M.-P.; Liao, H.; Montavon, G. Microstructural evolution and mechanical properties enhancement of a cold-sprayed Cu-Zn alloy coating with friction stir processing. *Mater. Charact.* **2017**, *125*, 76–82. [\[CrossRef\]](#)
65. Huang, C.; Li, W.; Zhang, Z.; Planche, M.-P.; Liao, H.; Montavon, G. Effect of Tool Rotation Speed on Microstructure and Microhardness of Friction-Stir-Processed Cold-Sprayed SiCp/Al5056 Composite Coating. *J. Therm. Spray Technol.* **2016**, *25*, 1357–1364. [\[CrossRef\]](#)
66. Peat, T.; Galloway, A.; Toumpis, A.; McNutt, P.; Iqbal, N. The erosion performance of cold spray deposited metal matrix composite coatings with subsequent friction stir processing. *Appl. Surf. Sci.* **2017**, *396*, 1635–1648. [\[CrossRef\]](#)
67. Ji, G.; Liu, H.; Yang, G.-J.; Luo, X.-T.; Li, C.-X.; Sun, Y.-F.; Zhu, S.-H.; Zhao, C. Improving Adhesion Strength and Electrical Conductivity of Cold-Sprayed Al Deposit on Cu Substrate Through Friction-Stir-Processing. *J. Therm. Spray Technol.* **2022**, *31*, 1813–1826. [\[CrossRef\]](#)
68. Ji, G.; Liu, H.; Yang, G.-J.; Luo, X.-T.; Li, C.-X.; He, G.-Y.; Zhou, L.; Liang, T. Formation of Intermetallic Compounds in a Cold-Sprayed Aluminum Coating on Magnesium Alloy Substrate after Friction Stir-Spot-Processing. *J. Therm. Spray Technol.* **2021**, *30*, 1464–1481. [\[CrossRef\]](#)
69. Khodabakhshi, F.; Marzbanrad, B.; Shah, L.H.; Jahed, H.; Gerlich, A.P. Friction-stir processing of a cold sprayed AA7075 coating layer on the AZ31B substrate: Structural homogeneity, microstructures and hardness. *Surf. Coat. Technol.* **2017**, *331*, 116–128. [\[CrossRef\]](#)
70. Yang, K.; Li, W.; Niu, P.; Yang, X.; Xu, Y. Cold sprayed AA2024/Al₂O₃ metal matrix composites improved by friction stir processing: Microstructure characterization, mechanical performance and strengthening mechanisms. *J. Alloys Compd.* **2018**, *736*, 115–123. [\[CrossRef\]](#)
71. Yang, K.; Li, W.; Xu, Y.; Yang, X. Using friction stir processing to augment corrosion resistance of cold sprayed AA2024/Al₂O₃ composite coatings. *J. Alloys Compd.* **2019**, *774*, 1223–1232. [\[CrossRef\]](#)
72. Huang, C.; Li, W.; Zhang, Z.; Fu, M.; Planche, M.-P.; Liao, H.; Montavon, G. Modification of a cold sprayed SiCp/Al5056 composite coating by friction stir processing. *Surf. Coat. Technol.* **2016**, *296*, 69–75. [\[CrossRef\]](#)
73. Han, P.; Wang, W.; Liu, Z.; Zhang, T.; Liu, Q.; Guan, X.; Qiao, K.; Ye, D.; Cai, J.; Xie, Y.; et al. Modification of cold-sprayed high-entropy alloy particles reinforced aluminum matrix composites via friction stir processing. *J. Alloys Compd.* **2022**, *907*, 164426. [\[CrossRef\]](#)

74. Yang, Z.; Wang, J.; Li, X.; Wang, Y.; Ni, D.; Zhang, X.; Xu, J.; Li, M. Improving the mechanical properties and electrical conductivity of cold-sprayed Cu-Ti₃SiC₂ composite by friction stir processing. *Compos. Part A Appl. Sci. Manuf.* **2023**, *173*, 107698. [\[CrossRef\]](#)
75. Sova, A.; Goriainova, I.; Feulvarch, E.; Giraud, L.; Peillon, N.; Borbely, A. Comparison between friction stir processing and laser remelting processes of cold sprayed metallic composite coatings. *Mater. Lett.* **2023**, *349*, 134898. [\[CrossRef\]](#)
76. Dzhurinskiy, D.; Babu, A.; Dautov, S.; Lama, A.; Mangrulkar, M. Modification of Cold-Sprayed Cu-Al-Ni-Al₂O₃ Composite Coatings by Friction Stir Technique to Enhance Wear Resistance Performance. *Coatings* **2022**, *12*, 1113. [\[CrossRef\]](#)
77. Khodabakhshi, F.; Marzbanrad, B.; Shah, L.H.; Jahed, H.; Gerlich, A.P. Surface Modification of a Cold Gas Dynamic Spray-Deposited Titanium Coating on Aluminum Alloy by using Friction-Stir Processing. *J. Therm. Spray Technol.* **2019**, *28*, 1185–1198. [\[CrossRef\]](#)
78. Huang, C.J.; Yan, X.C.; Li, W.Y.; Wang, W.B.; Verdy, C.; Planche, M.P.; Liao, H.L.; Montavon, G. Post-spray modification of cold-sprayed Ni-Ti coatings by high-temperature vacuum annealing and friction stir processing. *Appl. Surf. Sci.* **2018**, *451*, 56–66. [\[CrossRef\]](#)
79. Peat, T.; Galloway, A.; Toumpis, A.; Steel, R.; Zhu, W.; Iqbal, N. Enhanced erosion performance of cold spray co-deposited AISI316 MMCs modified by friction stir processing. *Mater. Des.* **2017**, *120*, 22–35. [\[CrossRef\]](#)
80. Boruah, D.; Ahmad, B.; Lee, T.L.; Kabra, S.; Syed, A.K.; McNutt, P.; Doré, M.; Zhang, X. Evaluation of residual stresses induced by cold spraying of Ti-6Al-4V on Ti-6Al-4V substrates. *Surf. Coat. Technol.* **2019**, *374*, 591–602. [\[CrossRef\]](#)
81. Gulizia, S.; Trentin, A.; Vezzù, S.; Rech, S.; King, P.C.; Jahedi, M.Z.; Guagliano, M. Characterisation of Cold Spray Titanium Coatings. *Mater. Sci. Forum* **2010**, *654–656*, 898–901. [\[CrossRef\]](#)
82. Ghelichi, R.; Bagherifard, S.; Parienete, I.F.; Guagliano, M.; Vezzù, S. Experimental study of shot peening followed by cold spray coating on residual stresses of the treated parts. *Struct. Durab. Health Monit* **2010**, *6*, 17–30.
83. Lu, F.-F.; Ma, K.; Li, C.-X.; Yasir, M.; Luo, X.-T.; Li, C.-J. Enhanced corrosion resistance of cold-sprayed and shot-peened aluminum coatings on LA43M magnesium alloy. *Surf. Coat. Technol.* **2020**, *394*, 125865. [\[CrossRef\]](#)
84. Zou, Y.; Qin, W.; Irissou, E.; Legoux, J.-G.; Yue, S.; Szpunar, J.A. Dynamic recrystallization in the particle/particle interfacial region of cold-sprayed nickel coating: Electron backscatter diffraction characterization. *Scr. Mater.* **2009**, *61*, 899–902. [\[CrossRef\]](#)
85. Tadge, P.; Gupta, P.K.; Sasikumar, C. Surface Nano-crystallization of AISI 304 Stainless Steel through Shot Peening Technique. *Mater. Today Proc.* **2015**, *2*, 3245–3250. [\[CrossRef\]](#)
86. Moridi, A.; Hassani-Gangaraj, S.M.; Vezzù, S.; Trško, L.; Guagliano, M. Fatigue behavior of cold spray coatings: The effect of conventional and severe shot peening as pre-/post-treatment. *Surf. Coat. Technol.* **2015**, *283*, 247–254. [\[CrossRef\]](#)
87. Yao, H.; Hu, X.; Yi, Z.; Xia, J.; Tu, X.; Li, S.; Yu, B.; Zhang, M.; Bai, X.; Chen, Q.; et al. Microstructure and improved anti-corrosion properties of cold-sprayed Zn coatings fabricated by post shot-peening process. *Surf. Coat. Technol.* **2021**, *422*, 127557. [\[CrossRef\]](#)
88. Khun, N.W.; Trung, P.Q.; Yeetan, A.W.; Sun, W.; Liu, E.; Butler, D.L. Effects of Shot Peening Pressure on Friction and Wear of High Pressure Cold Sprayed Ti-6Al-4V Coatings Under Dry and Lubrication Conditions. *Tribol. Ind.* **2023**, *45*, 472–486. [\[CrossRef\]](#)
89. Zhang, Q.; Li, C.; Li, C.; Yang, G.; Lui, S. Study of oxidation behavior of nanostructured NiCrAlY bond coatings deposited by cold spraying. *Surf. Coat. Technol.* **2008**, *202*, 3378–3384. [\[CrossRef\]](#)
90. Keymanesh, M.; Ji, H.; Tang, M.; Zhang, X.; Huang, K.; Wang, J.; Feng, P.; Zhang, J. Ultrasonic surface treatment techniques based on cold working: A review. *Int. J. Adv. Manuf. Technol.* **2024**, *134*, 4949–4979. [\[CrossRef\]](#)
91. Zhang, L.; Zhang, Y.; Wu, H.; Yang, S.; Jie, X. Structure and corrosion behavior of cold-sprayed Cu/Ni composite coating post-treated by ultrasonic shot peening. *SN Appl. Sci.* **2020**, *2*, 201. [\[CrossRef\]](#)
92. Takeda, K.; Matsui, R.; Tobushi, H.; Homma, S.; Hattori, K. Enhancement of Fatigue Life in TiNi Shape Memory Alloy by Ultrasonic Shot Peening. *Mater. Trans.* **2015**, *56*, 513–518. [\[CrossRef\]](#)
93. Yin, F.; Hu, S.; Hua, L.; Wang, X.; Suslov, S.; Han, Q. Surface Nanocrystallization and Numerical Modeling of Low Carbon Steel by Means of Ultrasonic Shot Peening. *Metall. Mater. Trans. A* **2015**, *46*, 1253–1261. [\[CrossRef\]](#)
94. Li, K.; He, Y.; Fang, C.; Ma, H.; Kim, J.; Lee, H.; Song, J.; Yang, C.; Lee, J.; Shin, K. Surface Nanocrystallization of Pure Cu Induced by Ultrasonic Shot Peening. *Nanosci. Nanotechnol.* **2014**, *14*, 9637–9643. [\[CrossRef\]](#)
95. Wu, X.; Tao, N.; Hong, Y.; Xu, B.; Lu, J.; Lu, K. Microstructure and evolution of mechanically-induced ultrafine grain in surface layer of AL-alloy subjected to USSP. *Acta Mater.* **2002**, *50*, 2075–2084. [\[CrossRef\]](#)
96. Su, H.; Luo, X.-B.; Chai, F.; Shen, J.-C.; Sun, X.-J.; Lu, F. Manufacturing Technology and Application Trends of Titanium Clad Steel Plates. *J. Iron Steel Res. Int.* **2015**, *22*, 977–982. [\[CrossRef\]](#)
97. Yu, C.; Qi, Z.-C.; Yu, H.; Xu, C.; Xiao, H. Microstructural and Mechanical Properties of Hot Roll Bonded Titanium Alloy/Low Carbon Steel Plate. *J. Mater. Eng. Perform.* **2018**, *27*, 1664–1672. [\[CrossRef\]](#)
98. Ren, Y.; Tariq, N.U.H.; Liu, H.; Cui, X.; Shen, Y.; Wang, J.; Xiong, T. An innovative and flexible approach to fabricate Mg/Al composite plates: Cold spraying and hot rolling post-treatment. *Mater. Sci. Eng. A* **2022**, *849*, 143515. [\[CrossRef\]](#)
99. Tariq, N.H.; Gyansah, L.; Qiu, X.; Du, H.; Wang, J.Q.; Feng, B.; Yan, D.S.; Xiong, T.Y. Thermo-mechanical post-treatment: A strategic approach to improve microstructure and mechanical properties of cold spray additively manufactured composites. *Mater. Des.* **2018**, *156*, 287–299. [\[CrossRef\]](#)

100. Zhao, Z.; Tariq, N.u.H.; Tang, J.; Jia, C.; Qiu, X.; Ren, Y.; Liu, H.; Shen, Y.; Du, H.; Cui, X.; et al. Microstructural evolutions and mechanical characteristics of Ti/steel clad plates fabricated through cold spray additive manufacturing followed by hot-rolling and annealing. *Mater. Des.* **2020**, *185*, 108249. [\[CrossRef\]](#)
101. Li, Z.; Yang, X.; Zhang, J.; Shan, A. Interfacial Mechanical Behavior and Electrochemical Corrosion Characteristics of Cold-Sprayed and Hot-Rolled Titanium/Stainless-Steel Couples. *Adv. Eng. Mater.* **2016**, *18*, 1240–1249.
102. Zhao, Z. Formation of nanoscale interface in a high-performance TA2/Q235 clad plate. *Mater. Lett.* **2024**, *355*, 135528. [\[CrossRef\]](#)
103. Jiang, T.; Tariq, N.; Qiu, X.; Zhang, Q.; Li, L.; Du, J. An effective approach to improve microstructure and tribological properties of cold sprayed Al alloys. *Rev. Adv. Mater. Sci.* **2023**, *62*, 20230314. [\[CrossRef\]](#)
104. Ren, Y.; Tariq, N.u.H.; Liu, H.; Cui, X.; Wang, J.; Xiong, T. Unraveling the effects of hot rolling on microstructure and mechanical properties of cold sprayed Mg/Al clad plates. *Mater. Today Commun.* **2022**, *33*, 104553. [\[CrossRef\]](#)
105. Zhao, Z.; Tariq, N.u.H.; Tang, J.; Ren, Y.; Liu, H.; Tong, M.; Yin, L.; Du, H.; Wang, J.; Xiong, T. Influence of annealing on the microstructure and mechanical properties of Ti/steel clad plates fabricated via cold spray additive manufacturing and hot-rolling. *Mater. Sci. Eng. A* **2020**, *775*, 138968. [\[CrossRef\]](#)
106. Xie, X.; Yin, S.; Raoelison, R.-N.; Chen, C.; Verdy, C.; Li, W.; Ji, G.; Ren, Z.; Liao, H. Al matrix composites fabricated by solid-state cold spray deposition: A critical review. *J. Mater. Sci. Technol.* **2021**, *86*, 20–55. [\[CrossRef\]](#)
107. Irissou, E.; Legoux, J.-G.; Arsenault, B.; Moreau, C. Investigation of Al-Al₂O₃ Cold Spray Coating Formation and Properties. *J. Therm. Spray Technol.* **2007**, *16*, 661–668. [\[CrossRef\]](#)
108. Qiu, X.; Tariq, N.U.H.; Qi, L.; Tang, J.-R.; Cui, X.-Y.; Du, H.; Wang, J.-Q.; Xiong, T.-Y. Effects of Dissimilar Alumina Particulates on Microstructure and Properties of Cold-Sprayed Alumina/A380 Composite Coatings. *Acta Metall. Sin. (Engl. Lett.)* **2019**, *32*, 1449–1458. [\[CrossRef\]](#)
109. Zhao, Z.; Tang, J.; Liu, H.; Liu, H.; Ren, Y.; Tong, M.; Yin, L.; Du, H.; Wang, J.; Xiong, T. Effect of rolling temperature on microstructure and mechanical properties of Ti/steel clad plates fabricated by cold spraying and hot-rolling. *Mater. Sci. Eng. A* **2020**, *795*, 139982. [\[CrossRef\]](#)
110. Qiu, X.; Qi, L.; Tang, J.-R.; Tariq, N.H.; Wang, J.-Q.; Xiong, T.-Y. A viable approach to repair neutron shielding B₄C/6061 Al composite sheets through cold spray and hot rolling co-treatment. *J. Mater. Sci. Technol.* **2022**, *106*, 173–182. [\[CrossRef\]](#)
111. Yao, W.; Tan, Y.; Lu, Q.; Yi, H.; Cheng, C.; Wu, L.; Saji, V.S.; Pan, F. Recent advances in protective coatings and surface modifications for corrosion protection of Mg alloys. *J. Mater. Res. Technol.* **2024**, *31*, 3238–3254. [\[CrossRef\]](#)
112. Johari, N.A.; Alias, J.; Zanurin, A.; Mohamed, N.S.; Alang, N.A.; Zain, M.Z.M. Anti-corrosive coatings of magnesium: A review. *Mater. Today Proc.* **2022**, *48*, 1842–1848. [\[CrossRef\]](#)
113. Campestrini, P.; Terryn, H.; Vereecken, J.; de Wit, J.H.W. Chromate Conversion Coating on Aluminum Alloys: III. Corrosion Protection. *J. Electrochem. Soc.* **2004**, *151*, B370. [\[CrossRef\]](#)
114. Kim, M.; Brewer, L.N.; Kubacki, G.W. Microstructure and corrosion resistance of chromate conversion coating on cold sprayed aluminum alloy 2024. *Surf. Coat. Technol.* **2023**, *460*, 129423. [\[CrossRef\]](#)
115. Jeffcoate, C.S.; Isaacs, H.S.; Aldykiewicz, A.J.; Ryan, M.P. Chromate in Conversion Coatings: A XANES Study of Its Concentration and Mobility. *J. Electrochem. Soc.* **2000**, *147*, 540. [\[CrossRef\]](#)
116. Blawert, C.; Dietzel, W.; Ghali, E.; Song, G. Anodizing Treatments for Magnesium Alloys and Their Effect on Corrosion Resistance in Various Environments. *Adv. Eng. Mater.* **2006**, *8*, 511–533. [\[CrossRef\]](#)
117. Dicu, M.; Matei, A.; Abrudeanu, M.; Ducu, C. Synthesis and properties of the porous titania coatings formed on titanium by plasma electrolytic oxidation for biomedical application. *J. Optoelectron. Adv. Mater.* **2011**, *13*, 324–331.
118. Vilardell, A.M.; Cinca, N.; Garcia-Giralt, N.; Müller, C.; Dosta, S.; Sarret, M.; Cano, I.G.; Nogués, X.; Guilemany, J.M. In-vitro study of hierarchical structures: Anodic oxidation and alkaline treatments onto highly rough titanium cold gas spray coatings for biomedical applications. *Mater. Sci. Eng. C* **2018**, *91*, 589–596. [\[CrossRef\]](#) [\[PubMed\]](#)
119. Lu, F.-F.; Ma, K.; Li, C.-X.; Li, C.-J. Enhanced Corrosion Resistance of a Double Ceramic Composite Coating Deposited by a Novel Method on Magnesium-Lithium Alloy (LA43M) Substrates. *J. Therm. Spray Technol.* **2021**, *30*, 680–693. [\[CrossRef\]](#)
120. Vilardell, A.M.; Cinca, N.; Pacheco, I.; Santiveri, C.; Dosta, S.; Cano, I.G.; Guilemany, J.M.; Sarret, M.; Muller, C. Hierarchical structures of anodised cold gas sprayed titanium coatings. *Trans. IMF* **2018**, *96*, 71–78. [\[CrossRef\]](#)
121. Dai, X.; Nan, J.; Si, Y.; Hu, J.; Song, S. Research on the corrosion behavior of sulfuric acid anodic oxidation layer of cold-sprayed pure aluminum coatings. *Powder Metall. Ind.* **2024**, *34*, 95–100. (In Chinese)
122. Zhang, Y. Preparation and Performance Research of Low-Pressure Cold Sprayed Aluminum-Based Coating—Anodic Oxide Film Composite Coating. Master's Thesis, Guangdong University of Technology, Guangzhou, China, 2021. (In Chinese).
123. Zarei, M.; Nourouzi, S.; Jamaati, R.; Cano, I.G.; Dosta, S.; Sarret, M. Formation of highly uniform tin oxide nanochannels by electrochemical anodization on cold sprayed tin coatings. *Surf. Coat. Technol.* **2021**, *410*, 126978. [\[CrossRef\]](#)
124. Zarei, M.; Nourouzi, S.; Jamaati, R.; Esmaeili-Faraj, S.H.; Cano, I.G.; Dosta, S.; Sarret, M. Electrochemical characterization of nanoporous SnO₂ formed by anodization on cold spray tin coating for supercapacitor application. *J. Electroanal. Chem.* **2023**, *931*, 117201. [\[CrossRef\]](#)

125. She, G.; Zhang, Q.; Han, Z.; Liu, Z.; Zhang, L.; Jie, X.; Tan, G.; Mo, L. Study on the microstructure and tribological properties of graphene reinforced cold spray—Anodic alumina-based composite coatings. *Surf. Technol.* **2024**, *53*, 133–141. (In Chinese)
126. Barati Darband, G.; Aliofkhaezai, M.; Hamghalam, P.; Valizade, N. Plasma electrolytic oxidation of magnesium and its alloys: Mechanism, properties and applications. *J. Magnes. Alloys* **2017**, *5*, 74–132. [\[CrossRef\]](#)
127. Cheng, Y.; Cao, J.; Peng, Z.; Wang, Q.; Matykina, E.; Skeldon, P.; Thompson, G.E. Wear-resistant coatings formed on Zircaloy-2 by plasma electrolytic oxidation in sodium aluminate electrolytes. *Electrochim. Acta* **2014**, *116*, 453–466. [\[CrossRef\]](#)
128. Martin, J.; Akoda, K.; Ntomprougkidis, V.; Ferry, O.; Maizeray, A.; Bastien, A.; Brenot, P.; Ezo'o, G.; Henrion, G. Duplex surface treatment of metallic alloys combining cold-spray and plasma electrolytic oxidation technologies. *Surf. Coat. Technol.* **2020**, *392*, 125756. [\[CrossRef\]](#)
129. Jovović, J.; Stojadinović, S.; Šišović, N.M.; Konjević, N. Spectroscopic study of plasma during electrolytic oxidation of magnesium and aluminium-alloy. *J. Quant. Spectrosc. Radiat. Transf.* **2012**, *113*, 1928–1937. [\[CrossRef\]](#)
130. Clyne, T.; Troughton, S. A review of recent work on discharge characteristics during plasma electrolytic oxidation of various metals. *Int. Mater. Rev.* **2018**, *64*, 127–162. [\[CrossRef\]](#)
131. Maizeray, A.; Marcos, G.; Cappella, A.; Planche, M.P.; Liao, H.; Henrion, G.; Czerwicz, T.; Martin, J. Effects of dispersed α -Al₂O₃ particles into a cold-sprayed aluminium coating on its subsequent oxidation by the PEO process. *Surf. Coat. Technol.* **2024**, *482*, 130713. [\[CrossRef\]](#)
132. Wen, L.; Wang, Y.; Zhou, Y.; Guo, L.; Ouyang, J.-H. Microstructure and corrosion resistance of modified 2024 Al alloy using surface mechanical attrition treatment combined with microarc oxidation process. *Corros. Sci.* **2011**, *53*, 473–480. [\[CrossRef\]](#)
133. Tazegul, O.; Muhaffel, F.; Meydanoglu, O.; Baydogan, M.; Kayali, E.S.; Cimenoglu, H. Wear and corrosion characteristics of novel alumina coatings produced by micro arc oxidation on AZ91D magnesium alloy. *Surf. Coat. Technol.* **2014**, *258*, 168–173. [\[CrossRef\]](#)
134. Tao, Y.; Xiong, T.; Sun, C.; Jin, H.; Du, H.; Li, T. Effect of α -Al₂O₃ on the properties of cold sprayed Al/ α -Al₂O₃ composite coatings on AZ91D magnesium alloy. *Appl. Surf. Sci.* **2009**, *256*, 261–266. [\[CrossRef\]](#)
135. Jing, Z.; Dejun, K. Effect of micro arc oxidation on micro—Structure and electrochemical corrosion performance of cold sprayed aluminum coating. *Anti-Corros. Methods Mater.* **2018**, *65*, 572–579. [\[CrossRef\]](#)
136. Yürektürk, Y. Modification of Cold-Sprayed Aluminum Coating on Nickel-Aluminum Bronze by Micro-Arc Oxidation. *J. Therm. Spray Technol.* **2021**, *30*, 1274–1283. [\[CrossRef\]](#)
137. Shao, M.; Wang, W.; Yang, H.; Zhang, X.; He, X. Preparation of Wear-Resistant Coating on Ti6Al4V Alloy by Cold Spraying and Plasma Electrolytic Oxidation. *Coatings* **2021**, *11*, 1288. [\[CrossRef\]](#)
138. Zhang, Y.; Wang, Q.; Ye, R.; Ramachandran, C.S. Plasma electrolytic oxidation of cold spray kinetically metallized CNT-Al coating on AZ91-Mg alloy: Evaluation of mechanical and surficial characteristics. *J. Alloys Compd.* **2022**, *892*, 162094. [\[CrossRef\]](#)
139. Rao, Y.; Wang, Q.; Oka, D.; Ramachandran, C.S. On the PEO treatment of cold sprayed 7075 aluminum alloy and its effects on mechanical, corrosion and dry sliding wear performances thereof. *Surf. Coat. Technol.* **2020**, *383*, 125271. [\[CrossRef\]](#)
140. Martin, J.; Maizeray, A.; Da Silva Tusch, C.; Marcos, G.; Czerwicz, T.; Henrion, G. A new strategy to prepare alumina-zirconia composite or multilayered coatings by combining cold-spray deposition and plasma electrolytic oxidation. *Mater. Today Commun.* **2023**, *36*, 106676. [\[CrossRef\]](#)
141. Yang, W.; Wang, J.; Xu, D.; Ke, P.; Li, J. Microstructure and properties of duplex coatings on magnesium alloy. *Surf. Eng.* **2016**, *32*, 601–606. [\[CrossRef\]](#)
142. Xin, S.; Song, L.; Zhao, R.; Hu, X. Phase composition and properties of the micro-arc oxidation coating on aluminium matrix composite. *Wuji Cailiao Xuebao/J. Inorg. Mater.* **2006**, *21*, 223–229.
143. Curran, J.; Clyne, B. Porosity in plasma electrolytic oxide coatings. *Acta Mater.* **2006**, *54*, 1985–1993. [\[CrossRef\]](#)
144. Yu, X.; Chen, L.; Qin, H.; Wu, M.; Yan, Z. Formation process of in situ oxide coatings with high porosity using one-step plasma electrolytic oxidation. *Appl. Surf. Sci.* **2016**, *366*, 432–438. [\[CrossRef\]](#)
145. Rao, Y. The Effects of Post-Processing on the Microstructure and Properties of Cold-Sprayed 7075 Aluminum Alloy. Master's Thesis, Hunan University, Changsha, China, 2021. (In Chinese).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.