

Review

Advanced Surface Protection Strategies for Refurbished Hydropower Components: A Critical Review of Chemical and Manufacturing Approaches

Gheorghe Daniel Lakatos ¹, Gabriella Stefánia Szabó ^{2,*} , Sára Ferenci ^{1,3}  and Loránd Szabó ^{3,*} 

¹ Institute for Research in Circular Economy and Environment “Ernest Lupan” (IRCCEM), 400561 Cluj-Napoca, Romania; daniel.lakatos@ircem.ro (G.D.L.); sara.ferenci@ircem.ro (S.F.)

² Department of Chemistry and Chemical Engineering in Hungarian, Babeş-Bolyai University, 400028 Cluj-Napoca, Romania

³ Department of Electrical Machines and Drives, Technical University of Cluj-Napoca, 400114 Cluj-Napoca, Romania

* Correspondence: gabriella.szabo@ubbcluj.ro (G.S.S.); lorand.szabo@emd.utcluj.ro (L.S.)

Abstract

This paper presents a critical review of surface protection strategies for refurbished hydropower components, with emphasis on the manufacturing and materials-processing logic that links damage mechanisms, substrate condition, deposition route, microstructure, and service performance. The literature indicates that cavitation erosion, sediment abrasion, corrosion, and their synergistic interactions are intensified by flexible and off-design hydropower operation, making refurbishment decisions increasingly surface-sensitive rather than purely bulk-material problems. Thermal spray and laser cladding remain the dominant industrially relevant routes, while cold spray and emerging multi-principal-element, high-entropy, and Fe-based amorphous systems expand the design space for lower heat input, better defect control, and improved cavitation resistance. Across the considered studies, the most consistent conclusion is that hardness alone is not a reliable selection criterion; porosity, interfacial integrity, crack susceptibility, residual stress, and the ability to accommodate local deformation govern real durability. Chemical pre-treatments, sealants, and hybrid finishing routes appear less mature as standalone hydropower solutions, but are important enablers for substrate activation, coating densification, and corrosion mitigation. Therefore, the review proposes a refurbishment-oriented framework in which route selection is based on the initial damage state of the component, the admissible thermal load on the substrate, the required build-up thickness, and the expected cavitation/slurry/corrosion regime.

Keywords: hydropower refurbishment; surface engineering; cavitation erosion; slurry erosion; thermal spray; laser cladding; cold spray; high-entropy alloy coatings; hydraulic turbines



Academic Editor: Shuo Yin

Received: 16 July 2026

Revised: 3 August 2026

Accepted: 6 August 2026

Published: 7 August 2026

Copyright: © 2026 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 \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Hydropower (HP) is the largest renewable electricity source worldwide [1]. It plays a critical role in grid stability and low-carbon energy transition strategies, representing the largest share of renewable electricity generation and contributing significantly to energy security and decarbonization pathways [2,3]. While traditionally considered a mature technology, HP is increasingly recognized as a key enabler for integrating intermittent

renewable sources such as wind and solar, owing to its inherent operational flexibility and rapid response capability under variable grid conditions [4–6].

Hydraulic turbines (HTs) are increasingly operated under transient and off-design conditions rather than steady-state regimes, including frequent load variations, start–stop cycles, and operation away from the best-efficiency point. These conditions introduce additional mechanical and hydraulic stresses that accelerate degradation processes and reduce component lifetime [7,8].

Among the various degradation mechanisms, surface-driven phenomena, particularly cavitation erosion (CE), sediment-induced abrasion, corrosion, and their synergistic interactions, are of primary importance, as they directly affect HT efficiency, reliability, and maintenance intervals [9–11]. Sediment-laden flows, especially in regions with high erosion potential such as mountainous or glacier-fed river systems, can significantly intensify material loss through particle impact, micro-cutting, and fatigue-related surface damage, often combined with cavitation effects that intensify surface degradation and material removal [12,13].

In parallel, the strategic importance of extending the service life of existing HP assets has shifted the focus toward refurbishment and remanufacturing approaches rather than full component replacement. From a sustainability and economic perspective, refurbishment strategies enable reduced material consumption, lower lifecycle costs, and improved resource efficiency [14,15].

Within this context, surface engineering emerges as a key enabling discipline for enhancing the durability and performance of refurbished HP components. Advanced coating technologies, chemical surface treatments, and manufacturing-based repair strategies are increasingly being developed and applied to mitigate degradation mechanisms and restore functional performance under severe hydrodynamic and tribological conditions [16–19].

Consequently, the integration of material science, surface chemistry, and advanced manufacturing approaches is essential to ensure reliable, efficient, and sustainable operation of HTs in modern energy systems.

1.1. Importance of Refurbishment in Hydropower

HP units are increasingly required to operate in flexible, fast-responsive, and off-design modes to balance grids with larger shares of intermittent renewable energy. This operating shift amplifies fatigue loading, transient hydrodynamic stresses, cavitation exposure, and maintenance pressure, while plant owners still need to retain efficiency, limit downtime, and avoid unnecessary replacement of large-value flow-passage components [8]. In parallel, sediment-laden rivers continue to accelerate erosion of runners, guide elements, nozzles, needles, and other wetted parts, especially in medium- and high-head installations. Under these conditions, refurbishment is not merely a maintenance action but a strategic life-extension pathway in which surface restoration and re-protection strongly influence remaining useful life, lifecycle cost, and operational reliability [7,12,16,20].

1.2. Significance of Protection in Hydro Turbine Refurbishment

Many critical HP failures are initiated or accelerated at the surface. Cavitation pits, slurry-cut grooves, corrosion-assisted crack nuclei, roughness growth, and coating delamination all change the local stress field and fluid–surface interaction, which in turn promote further damage and performance loss. Because these mechanisms act predominantly in the near-surface zone, refurbishment success depends heavily on whether the selected protection route can restore surface integrity, control defect populations, and preserve interfacial adhesion under repeated bubble collapse and particle-impact loading. The reviewed HT literature shows that protective layers are most effective when they simultaneously

combine adequate hardness with toughness, low porosity, and stable substrate/coating bonding [16,20,21].

1.3. Gap in the Literature

The available literature already contains useful reviews on lifetime reduction in flexible HP operation, sediment erosion in Pelton and other HTs, cavitation and silt erosion in hydraulic units, and the broader materials perspective on HT coatings. However, these bodies of work remain only partially integrated. Mechanism-focused reviews usually explain cavitation, erosion, or fatigue well, while coating reviews emphasize materials families and deposition methods. However, limited attention has been devoted to refurbishment-oriented decision-making frameworks: how the pre-existing damage state of a component, the admissible thermal input during repair, the substrate metallurgy, the desired build-up thickness, and field-practical constraints should determine the choice between thermal spray (TS), thermal cladding (TC), cold spray (CS), or hybrid chemical-assisted routes. This review addresses that gap by treating refurbishment as a process–microstructure–property–performance problem rather than as a simple list of candidate coatings.

The original contribution is the integration of three elements that previous reviews usually treat separately:

1. A damage-state-to-route decision logic for refurbished HP components;
2. A cross-technology comparison that links substrate, layer type, bonding mechanism, defect population, validation level, and refurbishment constraints;
3. A circular refurbishment (CR) interpretation in which durability is filtered through inspection, downtime, recoatability, and lifecycle value.

The review therefore does not aim to catalogue all possible coatings, but to provide a practical classification framework for selecting and qualifying surface-protection routes in refurbishment.

1.4. Scope and Contribution of This Review

This critical review focuses on refurbished HP components and evaluates surface-protection strategies through a CR lens, covering service damage, substrate condition, chemistry and interface stability, manufacturing route, performance, and decision criteria relevant to low-downtime lifetime extension.

2. Review Methodology and Analytical Framework

This manuscript adopts a critical review methodology rather than a bibliometric or systematic-review approach. The emphasis is on mechanistic interpretation and on the process–microstructure–property–performance relationships that determine whether a surface-protection route is suitable for refurbished HP components.

The analytical logic used throughout the review is summarized in Figure 1. The workflow starts from the dominant damage mechanisms and operating environment, then links these factors to substrate condition, protection-route selection, coating/interface microstructure, in-service performance, and final refurbishment decision-making. The feedback loop emphasizes that inspection, monitoring, and performance data should be used to refine future route selection and maintenance planning.

The technologies shown in the workflow are introduced here only as orientation points; their processing logic, advantages, and limitations are discussed in detail in Sections 5–8.

This framework reflects the fact that coating performance cannot be inferred from composition or hardness alone. Instead, durability depends on the interaction between process-induced defects, bonding state, residual stresses, substrate response, and the

mechanical behavior of the substrate–coating system under HP-relevant cavitation, slurry, corrosion, and fatigue loading.

Accordingly, manufacturing routes are treated as primary variables that shape functional performance, repair compatibility, inspection needs, and CR value.

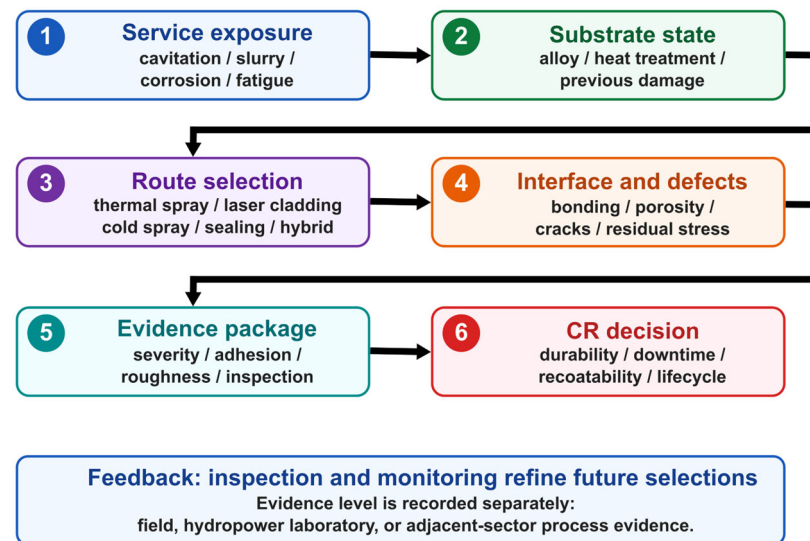


Figure 1. Scientific workflow for selecting surface-protection strategies for refurbished HP components.

2.1. Literature Search Strategy

The literature base was assembled through a targeted search on HP components, degradation mechanisms, and advanced surface-protection technologies, with emphasis on peer-reviewed studies that support comparison under refurbishment-relevant conditions.

Major scientific databases, including Scopus, Web of Science, and IEEE Xplore, were used to identify relevant work spanning materials science, surface engineering, and hydraulic machinery.

The final corpus covers HP lifetime analysis, sediment and cavitation damage, coating families for HTs, TS fundamentals, laser-clad anti-cavitation layers, CS restoration approaches, and emerging high-entropy alloy (HEA)/multi-principal-element alloy (MPEA) concepts.

Search terms included combinations of HT, runner, cavitation, slurry erosion, coating, TS, high-velocity oxy-fuel (HVOF), high-velocity air-fuel (HVOF), CS, TC, laser processing, HEA/MPEA, Fe-based alloys, corrosion, and fatigue.

The search encompassed literature available up to July 2026. The final cited corpus contains 100 references, including HP degradation and lifetime studies, cavitation–sediment–corrosion synergy papers, field- and plant-level erosion case studies, coating and surface-engineering reviews, primary experimental papers on TS, laser cladding (LC), CS, HEA/MPEA, and Fe-based amorphous systems, process-standard references, and adjacent-sector studies used only where they clarify transferable process principles. Because the review is critical rather than systematic, the number of initially screened records was not used as a ranking metric. Instead, priority was given to publications that provided mechanistic interpretation, processing details, quantitative performance indicators, engineering case relevance, or validation evidence relevant to HP refurbishment.

2.2. Inclusion and Exclusion Criteria

The included literature was required to satisfy at least one of the following conditions:

1. It addressed HP or hydraulic machinery damage mechanisms relevant to refurbishment;

2. It reported a protective or restorative surface engineering route with identifiable processing conditions;
3. It established a link between process, microstructure, and service performance;
4. Or it provided review-level synthesis directly applicable to HT components.

Studies from adjacent sectors were considered only when they clarified TS or coating-process principles transferable to HP applications. Pure bulk-alloy studies without a surface protection or refurbishment implication were excluded from the core synthesis.

Preference was given to studies reporting realistic loading conditions (cavitation, slurry erosion, or combined environments), as purely idealized laboratory tests often fail to capture the coupled degradation mechanisms observed in service.

2.3. Critical-Analysis Dimensions

Each protection strategy was assessed against a common grid: target degradation mode, substrate and pre-damage state, deposition route, bonding mechanism, characteristic defects, measured performance, post-processing needs, and implications for repair scale, downtime, and qualification.

This structured qualitative comparison enables cross-process interpretation despite differences in test methods, reporting practices, and performance metrics; no mathematical normalization, common index, or recalculation of reported data is applied.

2.4. Review Architecture and Decision Framework

A suitable critical review framework should therefore depict a decision sequence rather than a simple taxonomy. Service damage and operating regime first define the refurbishment need; substrate condition then constrains the allowable process window; the selected manufacturing route generates a characteristic interface and defect state; and only then can performance be evaluated in terms of cavitation resistance, slurry erosion, corrosion behavior, and expected durability.

This decision-oriented representation highlights that coating selection is not a material-only choice but a coupled materials–processing–application problem.

Such a framework makes explicit why the same nominal coating material may exhibit significantly different performance when deposited using different manufacturing routes or applied to substrates with different pre-existing damage states.

To make Figure 1 the structural backbone of the review, each subsequent technical section follows one or more elements of the workflow: Section 3 defines the damage mechanism and operating environment; Section 4 defines substrate condition; Sections 5–8 compare manufacturing routes, low-heat-input routes, and chemical/post-treatment steps; Sections 9 and 10 evaluate coating architecture, service performance, inspection, and qualification; and Section 11 converts these elements into refurbishment decisions.

2.5. Evidence-Level Interpretation

To avoid treating all evidence as equivalent, the review distinguishes four validation levels:

1. E1: direct HP field or industrial-component evidence;
2. E2: HP-relevant laboratory evidence using HT substrates, cavitation, slurry, corrosion, or mixed-mode testing;
3. E3: transferable process evidence from adjacent industrial sectors;
4. E4: conceptual, review-level, or standards-based evidence.

These levels are used qualitatively in the comparative tables and discussion to separate demonstrated HP applicability from laboratory ranking or adjacent-sector process plausibility.

3. Degradation Environment in Refurbished Hydropower Components

The degradation environment defines the boundary conditions for refurbishment because CE, slurry erosion, corrosion, fatigue, and their coupled forms act on surfaces already modified by service. Component location, turbine type, head, sediment burden, and operating flexibility determine both the dominant damage mechanism and the condition of the substrate presented for repair.

This section therefore translates the service environment into four refurbishment variables: exposed component, dominant degradation mechanism, damaged surface state, and required intervention depth. These variables provide the basis for the substrate and interface assessment developed in Section 4.

3.1. Component Classes and Operating Environments

The most exposed components include runners and runner blades in Francis and Kaplan units, Pelton buckets together with nozzles and needles in high-head plants, as well as guide vanes, stay vanes, wear rings, bottom rings, and labyrinth regions where pressure fluctuations, local acceleration, and particle-laden flow intensify damage [22].

For Pelton units, hydro-abrasive erosion is concentrated particularly in bucket cut-out, splitter, and brim regions, while injector degradation affects the nozzle outlet and needle-tip region; these locations are critical because erosion changes both local profile geometry and the quality of the water jet [22,23].

The severity and spatial distribution of erosion depend strongly on HT type and head range: Pelton turbines are especially sensitive in nozzles, needles, and buckets under sediment-laden high-head operation, whereas Francis units commonly experience erosion and cavitation on runner passages and associated flow-control surfaces [12,16,21].

For Francis turbines, combined reviews identify runner blades, guide vanes, and flow-passage surfaces as damage-prone regions, with severity controlled by sediment size and concentration, flow velocity, impingement angle, and local cavitation conditions [12,24–26].

3.2. Principal Damage Mechanisms

The principal mechanisms are CE, sediment or slurry abrasion, corrosion, erosion-corrosion and cavitation-corrosion synergy, together with fatigue-assisted degradation under fluctuating loading [7,27,28].

CE is driven by repeated bubble collapse, shock waves, and micro-jets, whereas sediment erosion is governed by particle impact, micro-cutting, ploughing, and roughness growth [24,25]. These mechanisms generate different damage morphologies, but their effects may converge when they act on the same wetted surface [20,21].

Key reviews emphasize that these mechanisms often coexist rather than act separately: sediment can alter local flow and intensify cavitation; corrosion pits and microcracks become preferential sites for mechanical attack; and flexible operation moves machines away from their best-efficiency operating zone, increasing transient loads and the probability of cumulative surface damage [7,12,16,21,29,30].

The combined cavitation-silt literature further indicates that coalesced damage is generally more severe than isolated cavitation or isolated sediment attack, because particle impact can remove strain-hardened layers while cavitation exposes fresh material and promotes crack growth under cyclic hydraulic loading [9,24,25].

3.3. Surface Condition of Components Before Repair

Before refurbishment, the damaged surface is rarely a simple worn plane. Reported morphologies include cavitation pits and craters, corrosion pits, oxide and corrosion-product deposits, shallow or deep spalling, roughness growth, localized delamination, crack

networks, corrosion-assisted cracking, and plastically deformed near-surface layers [31]. Because corrosion is widely observed in water-exposed HP components such as intakes, penstocks, isolation valves, scroll cases, wicket gates, turbine runners, draft tubes, spillways, and radial gates, it should be treated as a central pre-repair surface condition rather than as a secondary degradation mode [32].

Figure 2 presents a representative HT runner with severe service-induced degradation on the blade and hub surfaces. The image shows pronounced surface roughening, localized material loss, dark corrosion/oxide deposits, pitting-like attack, and irregular damaged zones on the blade surfaces. The non-uniform distribution of damage is consistent with combined hydraulic loading, where cavitation, sediment abrasion, corrosion-assisted attack, and fatigue-related surface degradation may interact. From a refurbishment perspective, such a surface cannot be treated as a simple worn plane: the damaged layer must first be assessed to determine whether cleaning and sealing are sufficient, whether a protective coating can be applied, or whether local excavation and rebuilding are required before re-protection.

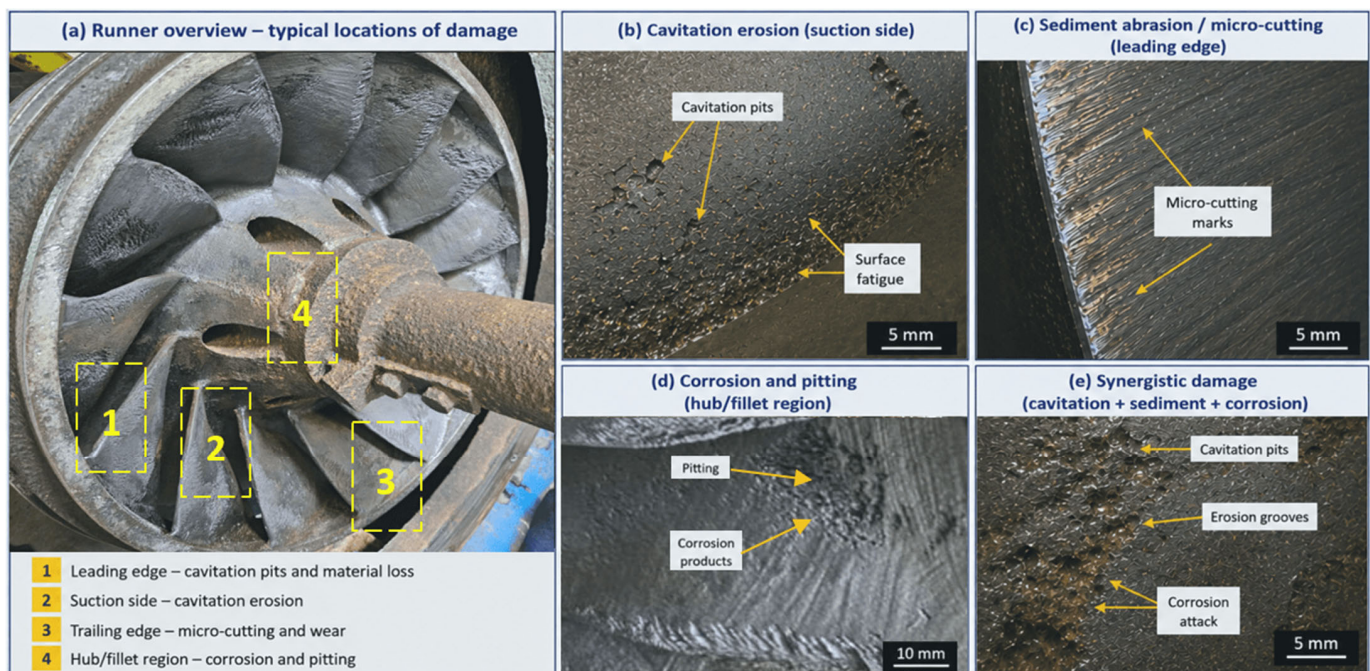


Figure 2. Illustrative montage of degradation morphologies on HT runner surfaces. Author photographs; locations withheld for confidentiality.

This pre-repair condition is critical because it determines whether the remaining surface can act as a stable substrate for a new protective layer or whether unstable material must first be removed. In coating systems, damage often initiates at pores or splat boundaries and propagates toward the interface. In substrates and dense clads, repeated cavitation loading can produce shear-band-dominated plastic deformation or shallow surface spalling before larger material loss occurs.

HT cavitation studies show that substrate and coating response depend on defect population, roughness evolution, and the ability of the material to accommodate localized plastic deformation without rapid crack propagation [20,33]. These pre-existing features are critical because they determine whether a route should primarily seal, protect, rebuild volume, or excavate and replace damaged material [20,34,35].

3.4. Damage-Driven Considerations for Refurbishment Route Selection

A key implication is that route selection must match both the substrate and the damage state. Thin protective coatings suit areas where geometry is largely intact and renewed cavitation or abrasion resistance is the priority, while heavily damaged regions with cracks, cavities, or section loss may require excavation and fusion-assisted rebuilding.

For example, a roughened but dimensionally intact runner passage may justify a dense sprayed coating or sealed overlay, whereas deep cavitation craters, crack networks, or section loss require removing unstable material before considering TC or another rebuild-capable process [16,20,35]. Low-heat-input routes are attractive when distortion or further metallurgical degradation must be avoided, though they may not provide the same build-up capability as TC.

Accordingly, the degradation environment should be translated into a repair decision sequence: identify the dominant mechanism, assess substrate stability, define whether protection or rebuilding is required, and then select a route whose bonding mode and thermal input are compatible with the damaged component.

Figure 3 summarizes this degradation-driven logic through a decision map linking service regime, dominant degradation mechanism, pre-repair surface state, refurbishment need, and suitable surface-protection route. The figure serves as a qualitative synthesis tool rather than a prescriptive selection chart. It emphasizes that coating, TC, CS, or hybrid sealing strategies should be chosen only after assessing damage morphology, substrate stability, thermal sensitivity, and the required extent of material rebuilding.

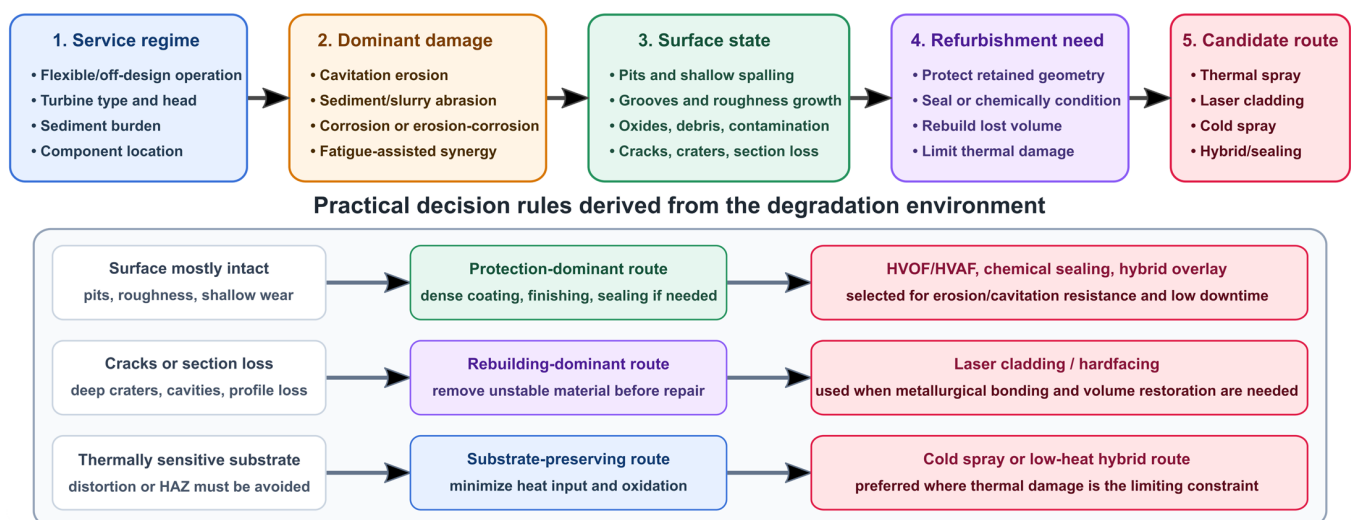


Figure 3. Damage-to-refurbishment decision map for HP components; this figure translates service regime and damage morphology into candidate refurbishment-route families.

4. Substrate Materials, Damaged Surface States, and Compatibility Issues

For refurbishment-oriented HP components, the substrate should not be considered a passive support structure. Its alloy class, heat-treatment condition, accumulated service damage, and tolerance to thermal or mechanical processing directly influence admissible repair windows, achievable bonding quality, residual stress development, and the most credible failure path during renewed service. In HP environments, these substrate characteristics evolve under cavitation, slurry erosion, and corrosion–fatigue, leading to strain hardening, residual stress accumulation, and progressive microstructural degradation [22,33,36].

For this reason, substrate characterization should include not only alloy designation and hardness, but also the near-surface damage state, prior thermal history, and the

expected bonding mechanism of the selected repair route. This is particularly important where cavitation loading has already modified the surface layer before any coating or rebuilding step is applied.

In practice, the same protection material may perform very differently depending on whether it is applied to a relatively intact martensitic stainless steel surface, a cavitation-damaged and strain-hardened region, or a previously repaired zone containing heterogeneity, oxide residues, or crack-like defects. Substrate roughness, grit-blasting conditions, and residual surface contamination strongly influence coating adhesion and interfacial integrity [37–39]. Consequently, delamination or localized spallation cannot always be attributed solely to the coating material, because substrate preparation and the resulting bonding conditions may also govern the observed failure path [40,41].

For that reason, substrate state must be evaluated together with coating chemistry and deposition route as an integral part of process selection and performance assessment.

4.1. Common Hydropower Substrate Alloys

HT runners, blades, and other wetted flow-passage parts are most often manufactured from martensitic or martensitic-austenitic stainless steels, with CA6NM and related 13Cr₄Ni or 13Cr₅Ni-Mo grades remaining especially important because they offer a practical compromise between strength, corrosion resistance, weldability, and cavitation tolerance.

These alloys exhibit tempered martensitic microstructures with retained austenite and carbide phases, which strongly influence their response to cavitation loading [42]. Under repeated micro-jet impacts, localized plastic deformation and strain hardening occur, followed by crack nucleation at phase boundaries and inclusions, ultimately leading to fatigue-driven material removal [42].

More specifically, CA6NM and 13Cr₄Ni steels should be regarded as dynamically evolving materials under service conditions rather than only as nominal base alloys. Low-temperature plasma nitriding of CA6NM has been reported to increase cavitation incubation time by about five to six times, attributed to nitrogen-expanded austenite formation in the treated layer [43,44]. A separate 13Cr₄Ni martensitic stainless steel study showed that ductility can delay fracture during CE and that hardness alone showed little relationship with cavitation resistance [45].

CE typically evolves from an incubation stage characterized by plastic deformation and surface hardening to an acceleration stage dominated by crack propagation and material detachment, confirming that degradation is governed by cyclic damage accumulation rather than instantaneous material loss [33].

In the recent HP coating literature, alloys such as 04Cr13Ni5Mo, ZG04Cr13Ni5Mo, ZG06Cr13Ni5Mo, and S135/06Cr13Ni5Mo recur as representative substrate materials for cavitation and repair studies, confirming that refurbishment solutions are still benchmarked against martensitic stainless steels of clear industrial relevance [16,20].

These substrates do not respond identically to protection routes. Fusion-assisted processing may alter heat-affected zones (HAZs), hardness distribution, and residual stress state [16,35,46]. In contrast, lower-heat routes rely more strongly on mechanical anchoring, interfacial cleanliness, and near-surface work hardening [47–49]. Consequently, substrate compatibility is not a secondary implementation parameter but a central design constraint for durable refurbishment [42].

This also means that the same repair temperature or surface-conditioning route can produce different outcomes depending on retained austenite stability, local work hardening, and pre-existing crack density. These variables should therefore be recorded when comparing coating performance across studies; differences attributed to coating chemistry may originate from substrate state.

The main substrate classes relevant to the reviewed refurbishment routes are summarized in Table 1. The table is intended to support process selection; exact mechanical values should be reported for the specific heat, casting, forging, welding, or previous repair condition of the component under study.

Table 1. Typical HP substrate classes and implications for refurbishment-route selection.

Substrate/Alloy Class	Typical Microstructure or Condition	Refurbishment-Relevant Properties to Report	Implications for Process Selection
CA6NM/ 13Cr4Ni martensitic stainless steels	Tempered martensite with possible retained austenite and carbide population; commonly used for runners and blades	Hardness, toughness/ductility indicators, heat-treatment state, prior welding or repair history, retained austenite stability, residual stress, cavitation-damaged layer depth	Compatible with TS where geometry is retained; LC/TC useful for section loss but HAZ, dilution, and residual stress must be controlled; CS is attractive where low heat input is required
13Cr-5Ni-Mo and related HT stainless steels	Martensitic or martensitic-austenitic stainless steels with improved corrosion/cavitation balance	Strength class, weldability, HAZ sensitivity, corrosion-pitting state, crack density, and surface work-hardening after service	Requires substrate-aware choice between protective overlay and rebuild-capable route; preparation depth and thermal input are critical
S135/ 06Cr13Ni5Mo-type stainless steels used in cavitation studies	HT-relevant martensitic stainless substrate used for comparative coating tests	Initial roughness, hardness, residual stress, porosity/crack state after damage, and mass-loss/roughness evolution under cavitation testing	Useful benchmark substrate for comparing HVOF/HVAF/LC routes; transfer to real components requires geometry and field-condition verification
Austenitic stainless steels such as 304L, used mainly as comparative or adjacent substrates	Austenitic matrix with higher ductility but different strengthening and corrosion response compared with martensitic HT steels	Ductility, work-hardening capacity, pitting/corrosion state, thermal expansion mismatch, and adhesion after immersion	Useful for mechanistic comparison, but direct translation to martensitic HT substrates should be justified rather than assumed

To support the cross-technology comparison requested in the review process, Table 2 summarizes the main refurbishment-route families using common qualitative criteria and the evidence-level scale defined in Section 2.5.

Table 2. Concise cross-technology comparison used to separate route family, substrate/layer type, bonding mechanism, defects, application window, and HP validation level.

Route Family	Typical Substrate/Layer Type	Bonding Mechanism	Typical Defects or Limits	Most Relevant HP Use Case	Hydropower Validation Level
HVOF/HVAF TS [16,20,50–59]	Martensitic HT stainless steels; WC-CoCr, Cr3C2-NiCr, Fe-based amorphous, and related cermet/metallic layers	Mainly mechanical interlocking and splat cohesion, influenced by particle velocity, temperature, and surface roughness	Porosity, oxides, splat boundaries, decarburization, residual stress, and adhesion sensitivity	Large-area cavitation/slurry protection where geometry is mostly retained and thermal load must remain moderate	Mainly E2 HP-relevant laboratory evidence, with broader E3 industrial maturity
Atmospheric plasma spray (APS), arc spray, and sealed TS systems [18,60–71]	Stainless steels or water-exposed steel surfaces; oxide, ceramic-metal, metallic, or sealed sprayed layers	Lamellar mechanical bonding plus sealing or densification where connected porosity is present	Higher connected porosity, oxide content, wet-interface degradation, and need for finishing/sealing	Barrier, corrosion-mitigation, or auxiliary protection where severe runner cavitation is not the only requirement	Mostly E3/E4 process and standards evidence; limited E2 severe-HT validation

Table 2. Cont.

Route Family	Typical Substrate/Layer Type	Bonding Mechanism	Typical Defects or Limits	Most Relevant HP Use Case	Hydropower Validation Level
LC/TC/hardfacing [16,20,35,46,72–76]	Martensitic stainless HT substrates; metallic, shape-memory alloy (SMA), HEA/MPEA, or carbide-reinforced clad layers	Metallurgical bonding with dilution and HAZ control	Cracking, dilution, HAZ changes, residual stress, distortion, and machining allowance	Local rebuilding, crater repair, contour restoration, or section-loss-dominated refurbishment	Strong E2 laboratory evidence for selected HT substrates; limited E1 field evidence
CS [16,34,47–49,77]	Substrate-sensitive metallic surfaces; metallic or composite solid-state deposits	Solid-state impact bonding, particle deformation, and interparticle cohesion	Incomplete bonding, porosity, retained particle interfaces, galvanic compatibility, and finishing requirement	Low-heat local restoration, substrate-preserving repair, or hybrid chains needing low thermal burden	Mostly E3 adjacent-sector process evidence, with emerging E2 HP-relevant validation
Chemical sealing, organic barriers, and hybrid post-treatments [63, 66,67,70,71,78,79]	Porous TS layers, repaired metallic surfaces, or lower-severity water-exposed zones; sealants, passivation, epoxy/polyurethane or hybrid barriers	Pore filling, wet adhesion, chemical barrier formation, or auxiliary interface stabilization	Water uptake, hydrolysis, sealant compatibility, insufficient mechanical load-bearing capacity, and recoatability	Auxiliary corrosion/fluid-ingress control, sealing of connected defects, and life-extension of mechanically resistant primary layers	Mostly E3/E4; should not be treated as standalone E1/E2 severe-cavitation evidence unless specifically demonstrated

4.2. Damaged Substrate Phenomena Relevant to Re-Protection

Before re-protection, the exposed substrate typically contains complex damage states beyond simple roughness, including cavitation pits, plastically deformed layers, microcracks, corrosion products, and embedded debris [20,33].

Accordingly, pre-repair assessment should distinguish between removable surface roughness, mechanically altered surface layers, and structurally relevant defects. Pits and shallow spalling may be treated by preparation and overlay, whereas connected cracks or deep craters change the repair problem from protection to rebuilding.

CE progresses through repeated high-pressure micro-jet impacts that generate localized high strain rates, dislocation accumulation, and subsurface crack growth, eventually leading to material spalling [20].

When combined with sediment erosion, particle impacts remove strain-hardened surface layers, exposing fresh material and accelerating degradation. This results in a synergistic interaction between erosion and cavitation mechanisms, producing significantly higher material loss than either mechanism alone [9,24].

These features modify local stress distributions and reduce effective load-bearing capacity, directly affecting coating adhesion and durability. In fusion-based repair routes, substrate dilution, remelting depth, and HAZ characteristics become decisive variables [35]. In sprayed systems, crack openings, contamination, and unstable damaged layers act as preferential sites for interfacial separation or fluid ingress during service [20].

The practical implication is that the refurbishment strategy must be matched to damage severity. Mildly affected regions may accept a protective overlay [16,20], whereas severely degraded regions, including extensive cavitation craters or crack networks, require excavation, local rebuilding, or metallurgically bonded repair solutions [35,46].

A useful reporting practice would therefore be to state the assumed pre-repair surface class for each protection route, for example, intact/roughened, plastically deformed, cracked, or section-loss-dominated. This would make comparisons between TS, LC, CS, and hybrid systems more meaningful for real refurbishment decisions.

4.3. Surface Preparation Before Protection

Although many studies emphasize coating performance more than preparation protocols, the evidence still points to surface preparation as a decisive stage in refurbishment quality.

A robust preparation sequence includes removal of unstable damaged material by machining or grinding, followed by cleaning and activation to eliminate oxides, oils, and corrosion residues [16,20]. Surface roughness is then tailored according to the intended bonding mechanism, particularly for sprayed coatings where roughness and grit-blasting conditions strongly influence adhesion and interfacial integrity [37–39]. Process-specific steps such as controlled preheating or defect opening may also be required before fusion-assisted repair routes.

TS adhesion literature supports this interpretation. Adhesion depends on a combination of mechanical interlocking, chemical interaction, and physical forces at the interface [40,41]. For HVOF coatings, substrate roughness and particle state are decisive: Wang reported that effective adhesion of HVOF NiCrBSi required an arithmetic mean surface roughness (Ra) above $\approx 1.7 \mu\text{m}$, while WC-Co bonding was strongly influenced by the solid–liquid state of incoming particles [37,80].

Surface preparation must be understood as an interface-engineering step, since coating performance depends not only on intrinsic material properties but also on the quality of interfacial bonding and defect minimization.

For this section, the key issue is preparation-specific rather than material-generic: surface roughness, cleanliness, retained damaged-layer depth, and defect opening determine whether the selected coating or rebuild route can develop a stable interface under renewed hydraulic loading [37–39].

Improper preparation can introduce embedded particles, residual stresses, or roughness gradients that act as stress concentrators and reduce coating durability [37–39]. For fusion-based routes, preparation also defines dilution behavior, fusion-line integrity, and susceptibility to cracking in the repaired zone.

For WC-Co TS coatings, grit blasting studies also show that increasing roughness through controlled blasting can improve adhesive behavior, but this must be balanced against the risk of embedded abrasive particles and roughness-induced stress concentration [38,39]. This is why preparation should be specified as a controlled process window rather than as a generic cleaning operation.

Therefore, inadequate removal of damaged layers or residual contamination can negate the intrinsic advantages of otherwise advanced protection systems [16,35].

The substrate-related variables discussed in this section can be summarized as an interface compatibility problem. Figure 4 illustrates how the pre-repair damage state controls the required preparation sequence, which in turn governs the bonding mode, defect population, and likely failure path of the refurbished surface.

Thus, Figure 1 defines the overall review workflow, Figure 3 converts damage state into route-family selection, and Figure 4 focuses on substrate preparation, bonding, and likely interface failure paths. Their roles were separated to reduce overlap among the graphical elements.

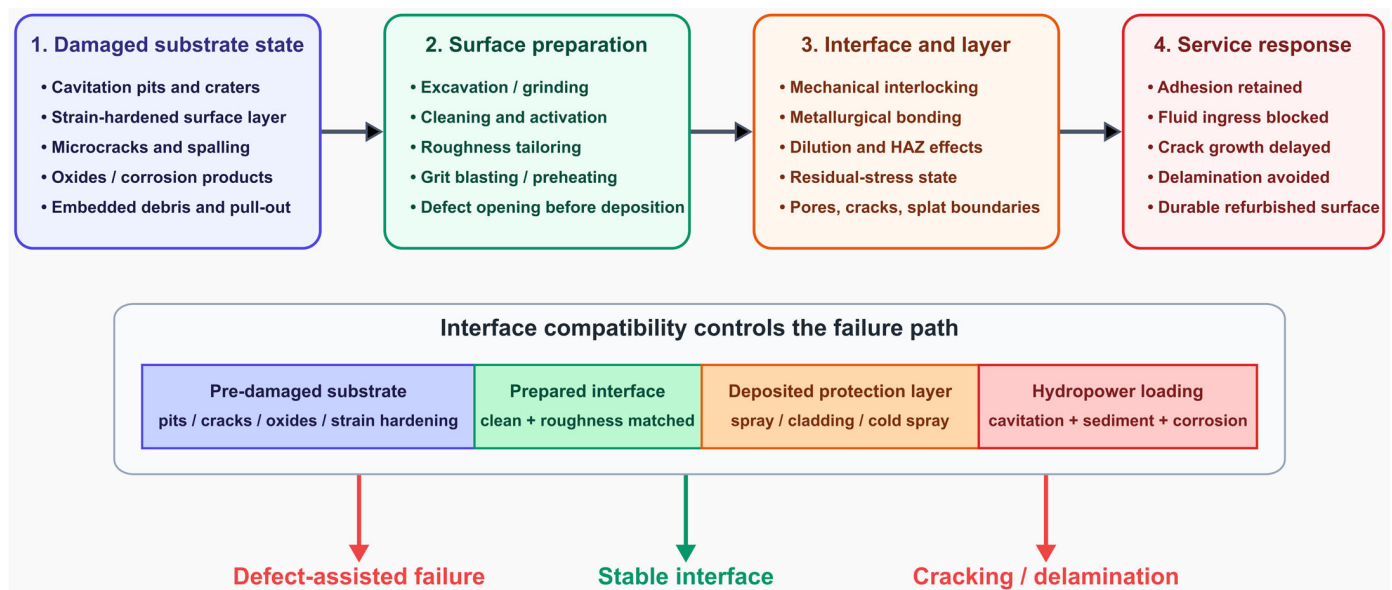


Figure 4. Substrate condition and interface compatibility map for refurbished HP components; this figure isolates the interface-control problem after the route family has been selected.

5. Thermal Spray-Based Protection Strategies for Refurbished Hydropower Parts

TS processes are evaluated here as refurbishment solutions rather than solely as coating technologies [81]. Their value depends on deposition logistics, surface preparation demand, achievable density and adhesion, finishing effort, inspection burden, and compatibility with the geometry of real HP components [50]. This shift from process listing to refurbishment applicability is essential for project relevance.

For this reason, the discussion of TS should be organized around process-controlled defect formation. Particle temperature, particle velocity, feedstock chemistry, substrate roughness, and post-treatment jointly determine whether the coating behaves as a dense protective layer or as a defect network susceptible to fluid ingress and cavitation-driven cracking.

TS remains one of the most industrially mature protection families for refurbished HP components because it can deposit hard, wear-resistant materials over large areas at thicknesses ranging from tens of μm to the mm scale, while keeping the thermal load on the substrate below that of fusion-based rebuilding. HT and general TS reviews consistently position this technology as a flexible and economical route for large components exposed to cavitation, slurry erosion, corrosion, and combined surface damage [18,60,61].

This maturity is especially relevant for refurbishment because large HP surfaces require scalable deposition, controllable thickness, and feasible finishing. However, industrial maturity does not guarantee reliability: sprayed coatings remain sensitive to surface preparation, porosity, oxide content, decarburization, and inter-splat cohesion.

5.1. Process Overview

The most relevant processes are HVOF, HVAF, APS, and, more selectively, arc-based spraying; CS belongs to the broader spray family but is treated separately here because of its solid-state deposition logic. General TS literature describes these routes in terms of different particle temperature–velocity windows, which translate directly into different defect populations and bonding characteristics. For HP, HVOF and HVAF are especially prominent because they enable dense carbide- and cermet-based deposits with relatively low porosity and good adhesion compared with many conventional alternatives [16,18,60,61].

From a refurbishment perspective, the practical distinction among spray processes is the particle thermal–kinetic balance. HVOF and HVAF are useful for dense carbide-based coatings because high particle velocity promotes compaction and adhesion, while the lower flame temperature of HVAF can reduce carbide degradation and improve toughness in WC-based systems. APS and arc spray routes are more relevant where oxide or metallic layers are desired, but their higher porosity usually increases the importance of sealing and post-treatment [50,60,61].

5.2. Coating Families

The dominant TS coating families reported for HT protection are WC-based cermets such as WC-CoCr, chromium carbide systems such as Cr₃C₂-based coatings, Fe-based amorphous coatings, and selected Ni-based or oxide-containing systems. The 2026 HT materials review places particular emphasis on cermets and Fe-based amorphous alloys as mature-to-emerging candidates, while the 2026 cavitation study on S135 steel directly compares HVOF-WC-10Co-4Cr, HVAF-WC-10Co-4Cr, HVOF-Cr₃C₂-based coating variants, and a laser-clad alternative under the same cavitation test framework [16,20].

The coating family should therefore be selected according to the dominant damage mode. WC-based cermets are attractive for abrasion and mixed erosion because of their hardness and mature processing. Cr₃C₂-based coatings are relevant where oxidation or corrosion resistance is also required, and Fe-based amorphous coatings are promising when corrosion resistance and reduced critical-material dependence are priorities [16,51,60].

5.3. Process–Microstructure Relationships

The performance of sprayed coatings is governed by microstructural features created during deposition: porosity, oxide content, decarburization, splat cohesion, residual stress state, and the integrity of the coating/substrate interface. The cavitation studies on HT coatings show clearly that pores act as damage initiation sites, while the broader review base explains why HVAF often outperforms HVOF for WC-based systems: lower flame temperature and more benign heating can reduce decarburization, lower porosity, and improve fracture toughness. Thus, the decisive variable is not nominal composition alone but the process-controlled defect architecture [20,52–54,82].

Substrate roughness must be optimized rather than simply maximized. HVOF bonding studies show that roughness influences mechanical anchoring and local contact, while excessive or poorly controlled blasting can introduce weak asperities, contamination, or residual stresses that reduce durability [37–39].

Adhesion assessment is also method-sensitive. Standard tensile adhesion tests, including ASTM C633-type testing [83], are useful for comparison, but their results can be affected by adhesive selection, specimen preparation, residual stress state, and whether failure occurs at the interface, within the coating, or in the adhesive layer [41]. Consequently, coating qualification should combine adhesion testing with cross-sectional porosity, crack-path analysis, roughness evaluation, and post-cavitation inspection.

To clarify the process-level differences within the TS family, Table 3 summarizes how major spray routes differ in particle state, defect architecture, coating families, and refurbishment relevance.

The reported temperature and velocity values are indicative ranges rather than fixed constants. They depend on torch design, fuel/oxidizer or plasma-gas chemistry, powder or wire composition, particle size and density, feed rate, stand-off distance, and component geometry. For APS, the temperature value refers mainly to the plasma gas or heat source, because particle temperature depends strongly on material properties and dwell time.

Table 3. TS process-microstructure-refurbishment relevance matrix for HP component protection.

Process Route	Particle/Thermal State	Typical Coating Families	Process-Controlled Microstructure or Defect Features	Refurbishment Advantages	Limitations and Qualification Focus
HVOF [16,20,50,51,55–57,82]	High-velocity combustion jet; typical in-flight particle velocity $\approx 600\text{--}800$ m/s; HVOF flame/source temperature commonly $\approx 2800\text{--}3000$ K	WC-CoCr, $\text{Cr}_3\text{C}_2\text{-NiCr}$, carbide/cermet systems, selected metallic alloys	Dense lamellar structure; possible decarburization, oxide formation, residual stress, splat boundaries, and local porosity	Strong candidate for large-area cavitation/slurry protection where high hardness and moderate thermal input are required	Requires strict roughness control, adhesion testing, porosity assessment, and post-finishing; failure may initiate at pores, weak splat boundaries, or residual stress-sensitive zones
HVAF [20,50–52,56]	High-velocity air-fuel jet; typical particle velocity $\approx 500\text{--}1200$ m/s; lower adiabatic flame temperature than HVOF, approximately 2100–2300 K	WC-CoCr and other carbide/cermet coatings require reduced thermal degradation	Lower oxidation and decarburization tendency; dense coatings with improved carbide retention and potential toughness benefit	Attractive for erosion/cavitation environments where carbide integrity, low defect density, and residual stress control are decisive	Requires process-specific qualification because performance depends strongly on powder state, stand-off distance, residual stress, and defect population
APS [18,54,57,60–62,84]	Very high-temperature plasma jet; plasma-gas/source temperature can reach $\approx 10,000$ K or higher, while typical particle velocities are commonly $\approx 100\text{--}300$ m/s	Oxides, ceramics, ceramic-metal systems, selected corrosion/wear barrier coatings	Higher porosity and oxide/splat-boundary content can occur; coating may require sealing or densification for wet service	Useful where ceramic or oxide-based barriers are needed and geometry allows controlled deposition	Less attractive as a standalone severe cavitation solution unless porosity, sealing, adhesion, and finishing are carefully controlled
Arc spray [63–65]	Electrically melted wire droplets atomized by gas flow; measured steel-droplet velocities are typically ≈ 100 m/s, with average droplet temperatures of $\approx 1925\text{--}2335$ °C	Metallic coatings, corrosion protection layers, stainless or alloyed wires	Lamellar structure with oxide content and porosity; adhesion and cohesion depend strongly on surface preparation and sealing	Economical option for large-area corrosion/wear mitigation and secondary or non-critical refurbishment surfaces	Not a primary route for severe runner cavitation; requires sealing, finishing, and careful qualification if used in water-exposed HT environments
Post-treated or sealed TS coatings [63,66–69]	Secondary chemical, thermal, or mechanical treatment after deposition	Sealed TS coatings, heat-treated WC-CoCr, remelted or densified layers	Can reduce connected porosity, improve cohesion, limit electrolyte ingress, and modify residual stress or surface integrity	Best treated as an enabling step for durability and corrosion protection rather than as an independent coating route	Requires verification of sealant penetration, coating compatibility, adhesion retention, and durability under cavitation/slurry exposure; cannot compensate for severe porosity, cracking, or weak bonding

5.4. Performance Under Hydropower Conditions

Under ultrasonic cavitation testing on S135 stainless steel, the compared coatings showed markedly different responses. The laser-clad layer achieved the lowest weight loss and smallest roughness increase, but among the TS routes, the HVAF-WC-10Co-4Cr and the Cr_3C_2 -containing HVOF coating outperformed the more porous HVOF-WC-10Co-4Cr variant [20]. A critical finding was that the hardest coating was not the best performer: the poorest cavitation resistance was observed in a coating with the highest microhardness because pre-existing pores and weak paths for crack propagation controlled failure. For

HP refurbishment, this confirms that cavitation, slurry erosion, corrosion resistance, and roughness retention should be judged together, not inferred from hardness alone [20,69].

Because the routes were evaluated on the same substrate and under the same cavitation framework, the study provides a useful benchmark showing that pore distribution, roughness evolution, and crack paths are more informative than microhardness alone [20].

The apparent contradictions between HVOF and HVOF performance should therefore be interpreted as process-window effects rather than as a universal ranking of one spray family over the other. Root causes include powder size distribution and carbide dissolution, flame temperature, particle velocity, oxidation/decarburization, residual stress state, substrate roughness, and the presence of connected pores or weak splat boundaries. Refurbishment decisions should therefore compare HVOF and HVOF coatings only when feedstock condition, spray parameters, substrate state, finishing roughness, and test method are reported together.

For TS routes specifically, the useful lesson is process-specific: coating density, splat cohesion, residual stress state, crack path, and pore distribution explain the observed cavitation response more directly than microhardness values alone.

5.5. Field Repair Practicality

From a refurbishment standpoint, TS is attractive for relatively large-area protection and for situations where excessive substrate heating is undesirable. It is also compatible with post-machining and finishing. Its limitations are equally clear: adhesion is not metallurgical in the same way as TC, coating integrity is highly sensitive to preparation and spray parameters, and severe cavitation can still cause local delamination or large-area spallation if porosity and inter-splat defects are not tightly controlled [16,18,20,60,61].

A refurbishment-oriented specification should therefore define not only coating material and thickness, but also substrate preparation, allowable porosity, adhesion requirement, finishing roughness, inspection method, and whether sealing is required. Without such process windows, laboratory cavitation or erosion gains may not translate into repeatable field performance.

6. Cladding-Based and Fusion-Assisted Protection Routes for Rebuilding and Localized Refurbishment

Cladding and related fusion-assisted routes are particularly relevant when refurbishment must do more than protect a surface and must instead rebuild locally lost material, restore contour, or create a metallurgically robust load-bearing surface. Consequently, their advantages need to be judged together with dilution, residual stress, heat-affected damage, machining demand, and downtime implications.

For a refurbishment-oriented review, the key distinction is that cladding is not only a protective coating route but also a geometry restoration route. It becomes most relevant when damage depth, section loss, or crack excavation requires the addition of load-bearing material, whereas thin coatings are more suitable when the original profile is still largely retained [16,35].

Cladding-based processes represent a second major category of refurbishment technologies because they combine protection with local rebuilding capability. Compared with sprayed layers, clads can provide denser deposits and stronger metallurgical bonding, which is particularly attractive when refurbished components already exhibit section loss or require local geometric restoration in addition to surface hardening.

6.1. Laser Cladding

LC is especially relevant in this context because it offers high power density, rapid solidification, low dilution relative to many conventional surfacing techniques, and the ability to generate dense coatings with strong metallurgical bonding. Studies repeatedly identify these features as key reasons why LC is attractive for hydraulic machinery and wetted flow-passage components. At the same time, the process must be controlled carefully because heat input, overlap strategy, and local thermal gradients can generate cracks, residual tensile stress, and distortion if the process window is poorly selected [16,35,46].

The practical performance of LC is governed by the coupled effects of energy density, powder-feed stability, overlap ratio, shielding, dilution, and cooling rate. These variables determine clad density, grain refinement, phase constitution, residual stress state, and the probability of solidification cracking; therefore, LC should be specified through a process window rather than by nominal alloy composition alone [16,35,46].

6.2. Advanced Laser Variants and Directional Energy Deposition Logic

Within the literature, the strongest evidence concerns conventional LC rather than a broad family of advanced beam variants. Even so, the underlying directional energy deposition logic is clear: localized energy input allows repair of selected damaged volumes, restoration of irregular surfaces, and compositional tailoring through feedstock design. This makes laser-based rebuilding particularly suitable for high-value HP components where complete replacement is undesirable, and the repair must be spatially targeted [16,35].

This point is important because several laser-based routes share the same refurbishment logic but differ in their material addition capability. Laser remelting can improve an existing surface without introducing a new feedstock, whereas powder-fed LC or directed-energy-deposition-like repair can rebuild damaged volumes and tailor chemistry locally. For refurbished HP components, the relevant decision is therefore whether the component needs surface reconditioning, protective overlay, or true volumetric rebuilding [16,35,72,73].

6.3. Typical Clad Material Systems

The papers taken into account document a broad materials spectrum for LC: Fe-based SMA coatings, CoCrNiAlTiNb HEA coatings, FeCrNiTiAlNb MPEA coatings, and the more traditional Co-, Ni-, or carbide-containing systems summarized in the HT coating review. This diversity is significant because it shows that cladding is not only a delivery route for classic hardfacing alloys but also a platform for microstructure engineering through phase balance, grain refinement, and precipitation control [16,35,46,74].

From a materials-selection perspective, these systems represent different strengthening philosophies. Fe-based SMA clads rely on deformation accommodation and phase-transformation-related strengthening; HEA and MPEA clads exploit phase balance, precipitation, grain-boundary engineering, and local deformation coordination; and conventional Co-, Ni-, Fe-, or carbide-containing clads provide more established hardfacing pathways. This diversity reinforces that the relevant design variable is not hardness alone, but the balance between hardness, toughness, crack resistance, corrosion stability, and compatibility with the substrate [16,35,46,74].

6.4. Cavitation and Corrosion Resistance of Clad Layers

The reported cavitation improvements of optimized clads are substantial. In the Fe-Mn-Si-Cr-Ni SMA coating, the accumulated mass loss rate after 5 h of cavitation was about 13% of that of the substrate, while the surface damage remained dominated by shear-band-like plastic deformation rather than extensive delamination. In the CoCrNiAlTiNb HEA study, the 3000 W condition produced the best performance, with 2.35 mg mass loss after 20 h and

an 88.89% reduction relative to the substrate. In the FeCr30Ni25Al5Ti5Nb-based MPEA coating, Nb-mediated grain-boundary engineering reduced 20 h mass loss to 1.35 mg, about 8.9% of the conventional martensitic stainless steel reference. Taken together, these studies show that cavitation resistance in clads depends on the ability to combine hardness with coordinated local deformation, crack suppression, and dense microstructures, not on hardness alone [35,46,74].

The quantitative results should be interpreted as evidence of a shared mechanism rather than as a simple ranking of alloys. The best-performing clads combine dense microstructures with controlled crack paths and sufficient local plasticity, allowing cavitation energy to be dissipated without rapid delamination. Conversely, a very hard clad may still perform poorly if dilution, brittle phases, tensile residual stresses, or interfacial defects dominate the failure path [35,46,74].

6.5. Limitations in Refurbishment Practice

Despite these advantages, LC is not universally superior. Dilution into the substrate, HAZ formation, residual stress, crack management, and distortion remain practical constraints, especially on large or thin-walled components. In addition, LC usually requires more localized process control and repair planning than sprayed coatings, and qualification becomes more demanding when different thermal histories, overlap zones, and rebuilt geometries are present within the same component [16,35,46].

Consequently, LC is most defensible when the refurbishment target includes local rebuilding, contour restoration, or a need for metallurgical bonding. It is less attractive for large areas with only shallow surface degradation, where TS or sealed TS systems may provide sufficient protection with lower heat input, easier coverage, and reduced machining demand [16,20,35].

7. Cold Spray and Other Solid-State/Low-Heat-Input Routes for Substrate-Preserving Refurbishment

Low-heat-input routes are attractive in CR because they preserve the substrate, limit thermal distortion, and facilitate repeated intervention with reduced collateral damage.

CS requires separate consideration because its solid-state deposition mechanism addresses a different refurbishment problem from TS and TC. Its solid-state deposition mechanism minimizes substrate heating and oxidation, which makes it attractive where thermal distortion, phase transformation, or heat-affected degradation of the base component must be avoided [16,34,47].

In this sense, CS should be treated as a substrate-preserving repair route rather than as a direct substitute for either TS or TC. Its value lies in solid-state deposition, limited oxidation, and reduced heat-affected damage, but its hydro-specific evidence base is still narrower than that of HVOF/HVAF coatings or LC [16,34].

7.1. Why Low-Heat-Input Routes Matter

In refurbished HP components, low-heat input is beneficial when the remaining substrate is geometrically sensitive, locally cracked, or metallurgically vulnerable to further thermal exposure. CS can therefore be attractive for adding material or protective layers to erosion-damaged regions without introducing the same extent of thermal damage associated with fusion-based routes [16,34].

Low-heat-input is particularly relevant for components that have already accumulated service damage, because additional thermal cycles may modify residual stresses, distort local geometry, or aggravate crack-sensitive regions. For repeated refurbishment cycles,

substrate preservation can therefore become as important as the maximum cavitation resistance of the newly deposited layer [16,34].

7.2. Cold Spray for Restoration and Protection

For CS, process relevance is governed by impact bonding, interparticle cohesion, retained thickness, and post-finishing condition rather than by a generic coating-family label.

For CS, this coupled interpretation is especially important because deposition depends on severe particle impact, plastic deformation, and interparticle bonding rather than droplet melting and resolidification. The coating quality is therefore governed by impact velocity, particle deformability, substrate hardness, surface activation, and post-deposition densification or finishing requirements [34,48].

Reinforcing an AA6061 matrix with Al-based quasicrystal particles reduces porosity, refines the microstructure to elongated nanometric grains, increases local nanohardness by more than 50%, and significantly reduces cumulative volume loss under CE. The associated references within that work also point to HP-oriented CS applications on stainless steel substrates, indicating that CS is emerging as a viable protection and restoration route for water-exposed components [34].

The relevance of this result for HP refurbishment is not that an Al-matrix composite is automatically a universal HT coating, but that CS can generate compacted, refined, and mechanically coherent layers without imposing a fusion thermal cycle. Transfer to actual HT steels would still require verification of galvanic compatibility, adhesion after immersion, cavitation/slurry durability, and finishing quality on curved or locally damaged substrates [34].

7.3. Bonding, Peening, Densification, and Post-Treatment

The beneficial response of CS coatings stems from their distinctive bonding mechanism: severe impact-induced deformation promotes interparticle cohesion and matrix strengthening rather than splat-based solidification [48,49].

In [34], improved cavitation behavior was linked to stronger particle/particle cohesion and a shift in damage from chunk detachment along weak boundaries toward more gradual and uniform material removal. This suggests that CS qualification should pay close attention to coating densification, local residual stress state, and any required machining or sealing after deposition.

This failure-mode shift is important for qualification. A coating that erodes gradually and uniformly may be more predictable in maintenance planning than one that fails by local chunk detachment or rapid interfacial separation. Therefore, CS evaluation should report not only volume loss but also crack morphology, cohesion, interface condition, residual porosity, and whether any sealant or post-treatment was required [34].

7.4. Comparative Niche vs. Thermal Spray and Cladding

CS is strongest where low thermal load and substrate preservation are the primary priorities. It is less well established than HVOF/HVAF or LC for severe HT cavitation service, and the literature evidence base for direct hydro-specific comparisons remains narrower. Accordingly, its most credible near-term niche is localized restoration or hybrid refurbishment, especially where conventional TC would impose excessive thermal burden and where conventional TS would not provide the same solid-state deposition advantages.

Overall, CS should be positioned as a complementary route within a refurbishment toolbox. It is promising for local restoration, low-heat deposition, and hybrid systems, but the present evidence does not yet justify presenting it as the primary solution for all severe cavitation or sediment-loaded HT surfaces. Its strongest near-term role is likely in substrate-sensitive zones, localized rebuilding before finishing, or combined systems where a CS

layer provides restoration and another route provides the final wear- or corrosion-resistant surface [16,34].

To synthesize the refurbishment role of fusion-assisted and low-heat-input routes, Table 4 compares their repair depth, thermal input, bonding logic, evidence base, practical advantages, and qualification risks for refurbished HP components.

Table 4. Comparative refurbishment logic for fusion-assisted and low-heat-input routes in HP component protection.

Route	Primary Refurbishment Role	Heat Input and Bonding Logic	Evidence/Material Systems	Main Advantages of Refurbishment	Limitations and Qualification Focus
LC/local rebuilding [16,35,46,74]	Local volume restoration, contour recovery, and creation of a dense protective surface where section loss or deep cavitation craters are present	Localized fusion with metallurgical bonding; rapid solidification can refine microstructure but introduces dilution, HAZ formation, residual stress, and thermal gradients	SMA and HEA clads; MPEA coatings; conventional Co-, Ni-, Fe-, and carbide-containing hardfacing systems	Combines rebuilding and protection in one route; strong bonding; high cavitation resistance when hardness, toughness, deformation accommodation, and crack suppression are balanced	Requires control of dilution, overlap strategy, cracking, residual tensile stress, distortion, machining allowance, and post-repair inspection; not always suitable for thin or thermally sensitive parts
Laser remelting/fusion-assisted surface reprocessing [16,72]	Surface reconditioning, densification, or modification where the original geometry is mostly retained, and extensive build-up is not required	Localized remelting of the surface or coating; metallurgical continuity can improve, but the process remains thermally intrusive	Laser-remelted stainless/cast stainless surfaces evaluated for corrosion and cavitation response; broader HT coating literature identifies remelting as a surface-quality improvement route	Can reduce near-surface defects, improve local integrity, and modify corrosion/cavitation response without depositing a thick new layer	Limited volume restoration capacity requires control of remelt depth, HAZ effects, cracking tendency, surface finish, and compatibility with the existing substrate condition
CS [16,34]	Substrate-preserving restoration or protective build-up where low thermal burden is the dominant constraint	Solid-state impact bonding through severe plastic deformation, peening, and particle/particle cohesion; minimal oxidation and limited thermal distortion	AA6061 matrix reinforced with Al-based quasicrystal particles showed reduced porosity, refined elongated nanometric grains, higher nanohardness, and lower cumulative cavitation volume loss	Attractive for thermally sensitive or geometrically delicate components; limits HAZ formation and phase transformation; suitable for localized restoration or hybrid repair chains	HP-specific evidence remains narrower than for TC or HVOF/HVAF; it requires verification of deposition efficiency, cohesion, porosity, residual stress, machining, and possible sealing
Hybrid rebuild-protection-sealing chains [16,20,34,35,66,67,74]	Function-distributed repair in which one route rebuilds volume, another provides cavitation and wear resistance, and post-treatment improves corrosion or fluid-ingress resistance	Combines metallurgical, mechanical, and chemical-interface mechanisms; thermal load and bonding mode depend on the selected sequence	Examples include TC followed by finishing, CS restoration followed by dense top protection, and TS layers supported by chemical sealing/densification	Allows the repair strategy to be matched to damage severity, substrate sensitivity, and service regime instead of forcing a single process to solve all requirements	More complex to qualify; requires compatibility between interfaces, thermal histories, sealants, residual stresses, inspection methods, and rework/re-coating routes

8. Chemical Perspective: Surface Protection and Chemical-Assisted Surface Modification Routes

In refurbished HP components, chemical treatments, sealants, passivation, and densification steps mainly act as interface-conditioning and defect-control measures. Their value is therefore linked to their integration with primary manufacturing routes, where they can improve surface activation, reduce electrolyte pathways, seal connected porosity, and enhance the durability of TS, TC, CS, or hybrid protection systems.

Organic coating systems, including epoxy, polyurethane, and elastomeric barrier layers, are acknowledged as relevant in selected water-exposed structures and lower-severity corrosion-protection contexts. However, the present review does not treat them as primary severe cavitation/slurry refurbishment solutions, because the reviewed evidence base and the main HT repair routes considered here are dominated by metallic, cermet, sprayed, clad, CS, and sealant-assisted systems. Organic systems are therefore discussed only as auxiliary barrier or sealing options where their adhesion, water uptake, wet aging, erosion tolerance, and compatibility with the underlying coating or substrate are explicitly qualified.

From a chemical standpoint, the relevant variables are wet-interface stability and barrier durability: adhesion mechanisms, hydrolytic stability, water uptake, corrosion protection chemistry, galvanic compatibility, and compatibility with sealants or bonded add-ons become central during prolonged submerged operation and repeated maintenance cycles.

In this review, chemical approaches are therefore treated as interface-conditioning and defect-management technologies. Their primary value is not to replace load-bearing coatings under severe cavitation or slurry attack, but to reduce electrolyte access, stabilize the coating/substrate interface, and improve the reliability of subsequent TS, TC, or hybrid protection routes.

The reviewed studies contain less HP-specific evidence on purely chemical protection routes than on TS and TC. Even so, chemistry remains important in refurbishment, mainly as a surface-conditioning, interlayer, sealing, or densification tool rather than as the primary load-bearing protection strategy [60,61].

This distinction is important for avoiding overclaiming: the strongest HP-specific evidence remains concentrated in TS, TC, and CS, whereas chemical routes mainly contribute through cleaning, activation, passivation, pore sealing, and corrosion-barrier functions.

8.1. Chemical Conversion and Passivation Strategies

For martensitic stainless substrates, chemical cleaning, activation, and passivation are relevant because HP damage is often aggravated by corrosion-assisted surface destabilization. The 2026 HT coating review notes that water chemistry and dissolved oxygen can trigger localized corrosion phenomena, which means that pre-deposition chemical treatment should be viewed not as a cosmetic step but as part of the interface engineering strategy. Proper chemical conditioning can reduce contamination and improve the reliability of subsequent protective layers [16].

For refurbished components, passivation is useful only after unstable, mechanically damaged layers, corrosion products, and embedded debris have been removed. Otherwise, local pits, oxide residues, and crack mouths can remain active electrolyte pathways and undermine the protective value of the passive film during renewed submerged service [16,85].

8.2. Electroless/Electrochemical Deposition Concepts

Electrochemical and electroless routes are more visible in general surface engineering literature. Their most plausible role here is as thin interlayers, bond-promoting deposits, or localized corrosion barriers where the required thickness is modest, and the geometry is accessible. However, studies also indicate why such routes are rarely sufficient as standalone refurbishment solutions for severe runner damage: the relevant operating environment combines cavitation, slurry attack, and repeated impact loading that generally demand thicker and mechanically more robust protection systems [16,61].

Their most credible refurbishment role is therefore local and functional: they can provide corrosion-barrier interlayers or bond-promoting deposits on accessible regions, but their limited thickness and mechanical load-bearing capacity make them vulnerable to

direct cavitation impact and sediment abrasion. For this reason, they should be evaluated as auxiliary layers within hybrid systems rather than as primary protection against severe hydraulic loading.

8.3. Sealants and Post-Deposition Densification Chemistry

A more immediately relevant chemical contribution is post-deposition sealing and densification. General TS reviews describe chromia-forming sealants, chemical slurry plus heating routes, and related strategies that reduce open porosity and improve corrosion resistance in sprayed coatings. For HP refurbishment, this suggests that chemical sealing is best understood as an auxiliary route used to stabilize porous coatings, limit fluid ingress, and reduce corrosion-assisted delamination, especially when the main protective layer is deposited by TS [18,60,61].

For Fe-based amorphous coatings, sealing treatment has likewise been reported to improve corrosion resistance in acidic solution by reducing the exposure of defect pathways and stabilizing the coating surface [66]. Although these systems are not direct HP demonstrations, they support the chemical logic relevant to refurbished hydraulic components: sealing is most useful when it complements a mechanically resistant primary layer by reducing fluid ingress and corrosion-assisted delamination.

The key mechanism is the reduction in connected porosity and capillary electrolyte pathways. Sealing treatments have been shown to improve the corrosion resistance of thermally sprayed ceramic coatings by blocking open defects and limiting electrolyte penetration [67]. A phosphate-based pore-sealing route applied to arc-sprayed Al coatings also improved corrosion resistance in artificial ocean water, illustrating the value of low-temperature chemical post-treatment for water-exposed metallic coatings [63].

8.4. Advantages and Limitations

The main advantages of chemical-assisted routes are low thermal load, limited distortion risk, and their usefulness for interface preparation or pore sealing. Their main limitation is that the literature evidence does not support them as full substitutes for thick, cavitation-resistant rebuild or protection layers in severe service. Accordingly, their strongest value lies in hybrid strategies rather than in standalone applications [16,60].

Accordingly, chemical-assisted protection should be qualified through indicators such as residual open porosity, water uptake or electrolyte penetration, adhesion retention after immersion, corrosion current or impedance response, and compatibility with the selected coating or rebuild route. This makes chemistry an enabling layer in the refurbishment chain rather than a standalone answer to cavitation and slurry erosion.

9. Emerging Material Chemistries and Coating Architectures

Emerging chemistries and hybrid architectures should be judged through a durability–repairability–sustainability lens rather than novelty alone, since their value depends on whether improved local performance can be translated into practical refurbishment benefit.

Beyond mature carbide and conventional hardfacing systems, recent work points to chemistry- and architecture-driven design aimed at balancing hardness, toughness, corrosion stability, processability, and reduced critical-material dependence.

For this review, the relevant question is therefore not whether an emerging chemistry is novel, but whether it solves a specific refurbishment limitation: reducing porosity, improving crack tolerance, lowering critical-material dependence, enabling recoatability, or stabilizing the interface in wet and particle-laden service. This screening logic helps prevent premature preference for complex alloys before their manufacturability and qualification evidence are sufficient.

9.1. Fe-Based Amorphous Coatings

Fe-based amorphous coatings are highlighted in a comprehensive review as a promising class because they can combine high hardness with corrosion resistance while reducing dependence on more expensive alloy systems. Their main challenge, as noted in that review, is not simply composition selection but achieving sufficient density and interfacial integrity in service-relevant coating architectures [16].

Their refurbishment relevance lies in the combination of corrosion-barrier potential, relatively high hardness, and possible reduction in Co- or Ni-intensive coating reliance. The main qualification risk is that amorphous or partially amorphous coatings can be sensitive to crystallization, porosity, residual stress, and brittle cracking when exposed to TS, finishing, or cavitation impact. For this reason, Fe-based amorphous systems should be treated as promising corrosion-wear architectures that still require careful control of density, sealing, and interfacial toughness before use as primary HP protection [16,66].

9.2. High-Entropy/Multi-Principal-Element Coatings

HEA and MPEA coatings emerge as one of the most dynamic directions in the field. The CoCrNiAlTiNb laser-clad coatings showed that laser power can tune precipitation behavior, hardness, wear rate, and cavitation response. The FeCrNiTiAlNb MPEA work further demonstrated that Nb microalloying, grain refinement, and increased face-centered cubic grain-boundary phase fraction improve local deformation coordination and dramatically reduce cavitation mass loss. These studies suggest that the value of HEA/MPEA coatings lies in phase-architecture control rather than in composition novelty alone [46,74,75].

These results are particularly relevant because they show how architecture-sensitive mechanisms, such as precipitation control, grain-boundary-phase distribution, and coordinated plastic deformation, can delay cavitation-induced crack growth. Nevertheless, the current evidence remains mainly coupon-level and process-specific. Before such coatings can be recommended for refurbishment practice, they need validation on HP-relevant substrates, repaired geometries, post-machined surfaces, and mixed cavitation-slurry-corrosion conditions [46,74].

9.3. Functionally Graded Coatings

The HT materials review identifies functionally graded coatings as a promising route because they offer a rational way to manage the property mismatch between the substrate and the wear-resistant surface. For refurbishment, such grading could reduce abrupt elastic and toughness discontinuities at the interface, although the key studies do not yet provide a comparably mature HP-specific dataset for graded cavitation-resistant systems [16].

The main refurbishment value of grading is the ability to distribute mismatches in hardness, elastic modulus, thermal expansion, and toughness across the coating thickness. In principle, a graded transition from a tougher substrate-compatible region to a harder wear-facing region could reduce stress concentration at the interface. In practice, however, this requires accurate control of feedstock composition, dilution, porosity, and thickness, and the evidence base remains less mature than for conventional clads or TS cermets [16].

9.4. Duplex and Multilayer Architectures

Layered and duplex architectures are relevant because barrier layers and tailored outer surfaces can redistribute stress and modify corrosion and wear paths. This logic is visible in [76], dealing with the plasma-sprayed AlCoCrFeNi/AT13 composite coating (in which AT13 denotes Al₂O₃–13 wt.% TiO₂), where introducing AT13 in dispersed or sandwich-like architectures altered internal stress distribution, lowered electrochemical reaction rate, and improved wear and corrosion behavior relative to the unmodified HEA

coating. Although not an HP-specific paper, it strengthens the case for multilayer design in future runner-protection systems [76,86].

For refurbished HT parts, a multilayer design is valuable only when the interfaces remain stable under repeated hydraulic loading. A ductile bond layer may improve compliance, a dense intermediate layer may reduce electrolyte ingress, and a hard outer layer may resist particle impact or cavitation; however, each additional interface also introduces a potential crack path or delamination plane. Therefore, multilayer systems should be evaluated by interfacial integrity and failure mode, not only by the properties of the outer layer [66,67,76].

9.5. Sealant-Assisted and Hybrid Architectures

Sealant-assisted and hybrid architectures should be treated as process chains rather than as independent coating labels. Their common purpose is to distribute functions across several steps: surface stabilization, volume restoration where needed, load-bearing protection, sealing of connected defects, final finishing, and future recoatability. This distinction is important for HP refurbishment because a single coating route rarely satisfies all requirements related to damaged substrate condition, cavitation/slurry resistance, corrosion protection, finishing, inspection, and downtime.

9.5.1. Sealant-Assisted Thermal-Spray Systems

Sealant-assisted TS systems are especially relevant when the primary sprayed coating provides the mechanical wear or cavitation barrier but still contains open or connected porosity. In such cases, sealing, chemical densification, heat treatment, or finishing can reduce capillary electrolyte pathways, improve corrosion resistance, and delay fluid-assisted degradation at pores, splat boundaries, and coating/substrate interfaces [51,63,66,67,69–71]. This logic is consistent with the role of sealants in thermally sprayed coatings, where the objective is not to replace the mechanically resistant coating but to improve its environmental stability by reducing connected defects and limiting electrolyte ingress [70,71].

For refurbished HP components, sealant-assisted systems should therefore be qualified by measurable indicators rather than by the presence of a sealant alone. Relevant reporting items include residual open or connected porosity after sealing, penetration depth or evidence of pore filling, adhesion retention after immersion or corrosion exposure, roughness after final finishing, compatibility between the sealant and the sprayed layer, and durability after cavitation, slurry, or corrosion testing. A sealed TS coating should not be considered suitable if the primary coating contains severe cracking, weak cohesion, poor adhesion, or excessive porosity, because sealing cannot compensate for a structurally defective coating.

9.5.2. Hybrid Process Chains for Refurbishment

Hybrid process chains are relevant when the damaged component requires more than one function from the repair route. Three practical cases are especially relevant for HP refurbishment:

1. Defect removal followed by LC or hardfacing and final grinding when section loss is present [35,46,73,75];
2. TS followed by chemical sealing, densification, heat treatment, or finishing when the primary coating is mechanically suitable but contains connected porosity or post-deposition defects [51,63,66,67,69–71,86];
3. CS restoration followed by finishing, sealing, or a harder top layer when substrate preservation and low heat input are the initial constraints [34,47–49]. Laser remelting may be considered only as transferable post-treatment evidence from adjacent CS

process studies, because the cited work concerns laser-remelted cold-sprayed Al coatings evaluated in 3.5% NaCl solution rather than HP-field validation [77].

In each case, the first step addresses substrate state or lost volume, the second step provides load-bearing or barrier function, and the final step controls roughness, porosity, fluid ingress, and future recoatability. The qualification challenge is that each additional interface also adds a possible failure path. Hybrid chains should therefore be reported with their sequence, thermal history, interlayer compatibility, final roughness, porosity/crack fraction, adhesion retention, and inspection method. Without this information, a hybrid route may appear superior in coupon testing while becoming difficult to repair, inspect, or repeat on a large runner or guide-vane surface [41,83,86,87].

10. Post-Processing, Finishing, Inspection, and Qualification After Protection

For refurbishment applications, post-processing and qualification are not secondary details. They strongly influence outage duration, cost, repeatability, and confidence in long-term service. A protection route that performs well in laboratory testing but requires impractical finishing or difficult inspection may be less attractive than a slightly lower-performing route with superior refurbishment logistics.

Post-processing and quality assurance are not peripheral steps in HP refurbishment; they directly influence whether the repaired surface will survive under cavitation and sediment attack. The considered literature repeatedly shows that damage often nucleates at pores, cracks, roughness peaks, or other defects that could, at least partly, be influenced by finishing and inspection [16,20].

Thus, post-processing should be considered part of the manufacturing route rather than a separate final operation. For HP refurbishment, the protected surface is successful only if the complete chain, substrate preparation, deposition, densification or sealing, finishing, and inspection, produces a stable surface that can retain adhesion under repeated cavitation, slurry impact, and wet corrosion exposure.

10.1. Finishing Operations

Grinding, polishing, profile restoration, and roughness control are particularly important because cavitation and slurry attack are sensitive to local flow disturbance and surface discontinuities. The recent HT cavitation study explicitly links roughness evolution to coating degradation, while the same paper notes the relevance of the new Guobiao recommended standard GB/T 43100-2023 guidance for post-treatment and finishing of TS coatings in demanding hydraulic applications [20,87]. Finishing should therefore be treated as a performance-critical step rather than as a purely cosmetic one.

The finishing requirement is process-specific. Laser-clad layers generally require machining or grinding to restore hydraulic profile and remove surface irregularities produced by overlapping tracks, whereas thermally sprayed layers require controlled grinding or polishing to reduce roughness peaks without exposing interconnected porosity. In sealed or hybrid systems, finishing must also preserve the continuity of the barrier layer; excessive material removal can reopen pores, compromise the chemical sealing function, or reduce future recoatability [16,20,66,67].

10.2. Inspection and Quality Control

Inspection should combine thickness, hardness, adhesion, porosity/crack analysis, surface roughness, and, where possible, residual stress-sensitive or cross-sectional verification of defect distribution. The Pelton review also highlights the practical role of non-destructive testing methods such as dye-penetrant and magnetic-particle inspection in maintenance

workflows. For HP refurbishment, qualification should move beyond simple coupon hardness toward a multiscale integrity assessment that explicitly checks the interface, the dominant defect population, and the likely damage initiation sites [7,12,16,20].

A staged inspection logic is preferable: before repair, the component should be classified by damage severity and substrate stability; after preparation, surface cleanliness, roughness, and defect opening should be verified; after deposition, thickness, porosity, cracking, and bond integrity should be checked; and after finishing, roughness and geometry restoration should be confirmed. This sequence is particularly important because the most likely failure path may shift from surface wear to interfacial separation if preparation or post-processing is inadequate [12,16,20].

10.3. Qualification Gaps in the Literature

A recurring weakness in the literature is the limited progression from short-term property data to qualification-oriented evidence under HP-relevant service conditions.

For refurbishment-oriented qualification, the minimum evidence package should therefore include the initial substrate condition, preparation route, coating thickness, porosity or crack content, adhesion or bond-quality evidence, finishing roughness, residual stress or HAZ assessment where relevant, and at least one HP-relevant durability indicator. Reporting these parameters together would make it easier to compare sprayed, clad, and hybrid systems beyond isolated hardness or short-duration mass-loss values [7,16,20].

To convert the qualification discussion into a practical reporting checklist, Table 5 summarizes the minimum evidence package that should accompany claims of coating or repair suitability for HP refurbishment. The table does not define a universal certification protocol, because allowable porosity, adhesion/cohesion strength, residual stress, roughness, thickness tolerance, and defect limits depend on HT type, component location, coating family, repair thickness, duty cycle, and inspection access. Instead, it identifies the route- and project-specific quantitative benchmarks or acceptance items that should be reported, including open or connected porosity, adhesion/cohesion strength and failure location, final roughness after finishing, connected-crack rejection limits, thickness and geometry-restoration tolerances, non-destructive testing criteria where applicable, and HP-relevant durability-test conditions.

Table 5. Minimum qualification evidence package for surface-protection systems used in refurbished HP components.

Evidence Dimension	Minimum Information to Report	Why It Matters for Refurbishment	Main Routes Affected	Indicative Quantitative Benchmark/Acceptance Item to Report
Substrate and pre-repair state [16,20,37,42,85]	Alloy/grade, heat-treatment condition, previous repair history, dominant damage class, cracks, pits, section loss, oxides, debris, and initial roughness	The same coating may behave differently on intact, strain-hardened, cracked, or previously repaired surfaces; substrate state controls admissible preparation and failure path	All routes	Report pre-repair roughness, pit/crater depth, crack presence, and removed material depth in μm or mm. For sprayed coatings, pre-deposition roughness should be specified because HVOF bonding can be strongly roughness-dependent; effective adhesion of HVOF NiCrBSi was reported only when substrate roughness exceeded approximately $R_a 1.7 \mu\text{m}$
Preparation and process window [37–41,53]	Cleaning/activation method, excavation or grinding depth, grit-blasting medium and pressure, roughness target, preheating if used, and key deposition parameters	Preparation controls interfacial contact, mechanical interlocking, contamination risk, dilution, crack sensitivity, and repeatability	TS, TC, CS	Report grit-blasting medium, pressure/distance where available, roughness target, and accepted contamination level. Preparation should be specified as a process window rather than as a generic cleaning step

Table 5. Cont.

Evidence Dimension	Minimum Information to Report	Why It Matters for Refurbishment	Main Routes Affected	Indicative Quantitative Benchmark/Acceptance Item to Report
Layer architecture and thickness [16,20,35,46,52,54,55,58,82]	Coating/clad/CS architecture, nominal and measured thickness, phase constitution, porosity, cracks, splat boundaries, dilution/HAZ, and gradient or multilayer design	Durability depends on defect architecture and interface quality, not nominal chemistry or hardness alone	TS, TC, hybrid systems	Report nominal coating/rebuild thickness, minimum local thickness after finishing, and thickness tolerance in μm or mm. Report total porosity and, where possible, open or connected porosity separately. For dense HVOF hardfacing/coating candidates, literature benchmarks include porosity <2%. Connected surface cracks should be reported as absent or below a project-defined rejection limit
Interface integrity and adhesion [40,41,53,55,58,83]	Adhesion test method, failure location, cross-sectional interface evidence, bond type, interfacial cracks, and adhesion retention after exposure, when possible	Interfacial separation, fluid ingress, and spallation are common limiting paths in submerged cyclic service	TS, sealed coatings, hybrid routes	Report adhesion/cohesion strength according to ASTM C633 or another declared method, together with failure location. For dense HVOF hardfacing/coating candidates, literature benchmarks include bond strength >70 MPa. ASTM C633 results should be interpreted together with coating thickness, failure location, and adhesive-penetration risk
Post-processing and finishing [20,66–68,87,88]	Grinding/polishing route, final roughness, sealing or densification treatment, heat treatment/remelting, residual stress mitigation, and profile restoration	Finishing controls flow disturbance, roughness-driven cavitation sensitivity, connected porosity, and corrosion-assisted delamination	TS, TC, sealed systems	Report arithmetic mean roughness (Ra) and maximum profile height (Rz) before deposition and after finishing. For cavitation comparisons, identical or controlled surface preparation should be used because ASTM G32 notes that cavitation results can be significantly affected by specimen surface preparation
HP-relevant durability testing [9,20,24,50,55,84,88–90]	Cavitation, slurry erosion, corrosion, or combined tests; duration; liquid chemistry; sediment size/concentration; impact angle/velocity; mass loss; roughness evolution; post-test crack path	Isolated short-term tests cannot represent HT exposure unless the relevant damage mechanism and severity are clearly defined	All routes	Report mass loss, volume loss, maximum erosion rate, incubation time where measurable, test duration, medium, temperature, sediment size/concentration, impact velocity or angle, and comparison against an uncoated/reference substrate. Acceptance should be expressed as required percentage improvement or maximum allowed loss under identical test conditions
Inspection and quality control [7,12,16,20]	Thickness, hardness, porosity/crack fraction, surface roughness, non-destructive testing where applicable, residual stress-sensitive evidence, and acceptance/rejection thresholds	Coupon performance must be converted into inspectable criteria suitable for field or workshop refurbishment	All routes	Report non-destructive testing method where applicable, minimum detectable defect size where available, and explicit rejection criteria for connected cracks, delamination, lack of bonding, or under-thickness region
Refurbishment practicality and circular value [7,8,91]	Repair location, accessibility, downtime, recoatability, removed material volume, expected maintenance interval extension, life-cycle assessment/life-cycle costing, or circularity indicator when available	The best route is the one that balances durability with reparability, downtime, lifecycle burden, and cost per service-life extension gained	All routes, especially hybrid chains	Report repair time, number of process steps, dismantling requirement, post-machining time, recoatability after renewed damage, and expected service-life or maintenance-interval extension. If exact cost data are unavailable, this absence should be stated as a qualification gap

Table 6a,b separate material/process indicators from test response and transferability. Values are reported only where the reviewed sources provide comparable data; otherwise, the limitation is stated. The E1–E4 labels defined in Section 2.5 identify the evidence level.

Table 6. (a) Material and process indicators for representative surface-protection systems. (b) Test response and transferability limits for the same systems. Bold type indicates the main validation level (E1–E4) assigned to the corresponding study or process route.

(a)			
Reported Material/Process Indicators		Substrate and Layer	System/Route and Validation Level
Dense HVOF benchmark: porosity <2%; bond strength >70 MPa [58]. Hardness alone did not predict response [20]		S135/06Cr13Ni5Mo-type HT stainless steel; carbide/cermet TS and LC layers	HVOF/HVAF WC-CoCr and Cr3C2 coatings vs. LC [20,58,82,84,92] E2
Thickness and adhesion were not comparable with TS datasets; crack suppression and deformation accommodation governed response		SMA LC on steel	Fe-Mn-Si-Cr-Ni SMA LC [35] E2/E3
Laser power controlled hardness and microstructure; thickness/adhesion were not comparable with TS/CS data		HEA LC on steel; power-dependent microstructure	CoCrNiAlTiNb HEA LC [46] E2/E3
Dense clad; specification-level thickness and adhesion were not reported		MPEA/HEA-type laser-clad layer	FeCr30Ni25Al5Ti5Nb MPEA LC [74] E2/E3
Low porosity, intimate interface, grain refinement, and hardness above 316 stainless steel (SS316) [93]		Cold-sprayed metallic/cermet deposits on SS316	CS SS316, Inconel 625, and CrC-NiCr [93] E2/E3
Lower porosity, refined microstructure, and >50% higher nanohardness [34]		Cold-sprayed Al-matrix composite; HP relevance inferred from CE response	CS AA6061 + Al-based quasicrystal [34] E3/E2
Amorphous fraction, porosity, oxides, and interface state depended on spray power and post-treatment [94,95]		Plasma- or arc-sprayed Fe-based amorphous coatings; optional remelting/sealing	Fe-based amorphous/laser-remelted arc-sprayed coatings [66,68,94,95] E2/E3
Thickness and adhesion varied with formulation and preparation; mainly barrier or pore-sealing layers		Polymeric or ceramic-organic barriers/sealants, alone or over-sprayed coatings	Organic/ceramic-organic barriers or sealants [78,79] E3/E4
(b)			
Transferability Limit	Reported Response	Test Condition	System/Route and Validation Level
Match particle loading, roughness, curvature, preparation, and defect acceptance	Cavitation weight loss vs. S135: HVOF-WC10Co4Cr 1.58x; HVAF-WC10Co4Cr 0.88x; HVOF-Cr3C2 0.91x; LC 0.34x [20]. Coated CF8M also showed lower slurry loss [92]	Ultrasonic CE; related slurry tests with variable concentration/impingement [20,92]	HVOF/HVAF WC-CoCr and Cr3C2 coatings vs. LC [20,58,82,84,92] E2
Field durability, dilution, cost, and repeated repair remain insufficiently documented	Mass-loss rate was about 13% of the uncoated substrate [35]	Ultrasonic CE, 5 h	Fe-Mn-Si-Cr-Ni SMA LC [35] E2/E3
Coupon-scale evidence; mixed-mode, large-component, and recoatability validation remain limited	Optimized condition: 2.35 mg loss, 88.89% below the reference [46]	Ultrasonic CE, 20 h	CoCrNiAlTiNb HEA LC [46] E2/E3

Table 6. Cont.

(b)			
Transferability Limit	Reported Response	Test Condition	System/Route and Validation Level
Scale-up must control dilution, residual stress, cracking, cost, and inspection	Mass loss: 1.35 mg, about 8.9% of the reference [74]	Ultrasonic CE, 20 h	FeCr30Ni25Al5Ti5Nb MPEA LC [74] E2/E3
HT-steel use needs adhesion, immersion, galvanic, curvature, and finishing validation	Both deposits outperformed SS316; Inconel 625 gave nearly fourfold improvement [93]	Cavitating liquid jet, ASTM G134 [93]	CS SS316, Inconel 625, and CrC-NiCr [93] E2/E3
Not universal for HT steel; compatibility under severe slurry/corrosion must be verified	CE cumulative volume loss was significantly reduced [34]	CE test reported in the source	CS AA6061 + Al-based quasicrystal [34] E3/E2
Field data are limited; remelting adds heat input, residual stress, and cost	After remelting, CE-corrosion mass-loss rate fell by 77.84% vs. as-sprayed coating [95]	CE/CE-corrosion in water or 3.5 wt.% NaCl [66,68,95]	Fe-based amorphous/laser-remelted arc-sprayed coatings [66,68,94,95] E2/E3
Not standalone protection for severe runner cavitation/slurry loading	Barrier/pore sealing improved, but results were not directly comparable with TS or LC [78,79]	Severe-runner cavitation/slurry evidence was indirect; laboratory CE evidence exists [78]	Organic/ceramic-organic barriers or sealants [78,79] E3/E4

11. Comparative Critical Assessment of Protection Strategies from a Circular Refurbishment Perspective

Sections 3–10 show that surface protection for refurbished HP components should be evaluated as an integrated system involving service damage, substrate condition, manufacturing route, interface quality, and lifecycle considerations. Hence, the comparison cannot be reduced to a ranking of coating hardness or short-term mass loss. A route that performs well on a polished coupon may be unsuitable for a cracked, strain-hardened, geometrically sensitive, or previously repaired HT surface if it imposes excessive thermal load, cannot rebuild lost volume, or cannot be inspected and reworked reliably.

The central comparative logic is damage-led. The service environment defines whether the primary need is cavitation resistance, slurry erosion resistance, corrosion mitigation, profile restoration, or combined protection. The pre-repair surface then defines whether the feasible intervention is sealing/protection, local rebuilding, low-heat restoration, or a hybrid chain. This logic connects the degradation map, substrate compatibility discussion, interface-chemistry section, and process-specific evidence developed earlier in the review.

11.1. Route Suitability by Degradation Mechanism

For dominant cavitation, the strongest direct evidence in the reviewed set is associated with dense laser-clad systems and selected optimized TS coatings. The laser-clad SMA, HEA, and MPEA systems show that cavitation resistance improves when hardness is combined with deformation accommodation, crack suppression, dense microstructure, and stable bonding [35,46,74]. For slurry or mixed particle erosion, HVOF/HVAF carbide-based systems remain highly relevant because their maturity, hardness, and dense microstructure make them suitable for large-area protection where geometry is largely retained [20,50,55,82,84].

For corrosion-assisted or erosion-corrosion conditions, selection becomes more sensitive to porosity, sealing, chemistry, and interfacial stability. Fe-based amorphous systems,

sealed TS coatings, and hybrid barrier architectures are attractive in this space, but the evidence is less mature for direct HP deployment than for cermet TS or LC [16,66,67].

11.2. Route Suitability by Refurbishment Constraint

When the component is lightly damaged, and the hydraulic profile is largely retained, TS and sealed TS systems are often the most practical choices because they provide large-area coverage, moderate heat input, and comparatively mature industrial know-how [16,18,50,60,61]. When local cavities, deep cavitation craters, or section loss are present, LC becomes more credible because it can restore volume and provide metallurgical bonding [16,35,46].

When the remaining component is thermally sensitive, locally delicate, or at risk of distortion, CS has a clearer role because it offers solid-state deposition and limited thermal damage [16,34]. Chemical sealing, passivation, and densification routes should be treated as enabling steps rather than as primary severe-service protection, because their main contribution is to stabilize interfaces, reduce electrolyte pathways, and support more robust coating or repair systems [63,66,67].

11.3. Manufacturing and Qualification Balance

To reduce the subjectivity of maturity statements, this review uses a refurbishment-oriented maturity interpretation alongside the narrative assessment: TRL 3 corresponds to laboratory proof of concept on coupons; TRL 4 to validated coating formation and damage testing on representative substrates; TRL 5 to testing under HP-relevant cavitation/slurry/corrosion severity; TRL 6 to component-relevant geometry or workshop-scale demonstration; and TRL 7 or higher to field or near-field validation with inspection and maintenance feedback. On this basis, HVOF/HVAF coatings are treated as the most mature broad-area protection routes, LC as mature for local rebuilding when thermal effects are controlled, CS as promising but less mature for severe HT exposure, and hybrid/HEA/MPEA routes as lower-maturity options unless validated beyond coupon scale.

The manufacturing comparison is governed by bonding mode and defect tolerance. TS depends on mechanical interlocking, splat cohesion, porosity control, and post-treatment. TC provides metallurgical bonding and build-up capacity, but introduces dilution, HAZ formation, residual stress, and machining requirements. CS reduces thermal risk but still requires verification of cohesion, porosity, residual stress, and adhesion after immersion. Hybrid chains can distribute functions across steps, but they increase qualification complexity because each interface becomes a potential failure path [34,35,37,40,41].

A refurbishment-oriented choice should therefore weigh not only performance under cavitation or slurry exposure, but also surface preparation burden, field or workshop repeatability, inspection accessibility, finishing demand, and the likelihood that the same component can be reworked in a future maintenance cycle.

11.4. Practical Circular-Refurbishment Constraints: Cost, Downtime, Repairability, and Recoatability

For CR, practical viability should be reported using measurable route-level indicators rather than general claims of sustainability. These indicators include removed material volume, coating or rebuild thickness, preparation effort, number of deposition and post-processing steps, need for component dismantling or possibility of in-situ repair, post-machining requirement, inspection burden, expected recoatability after renewed damage, expected maintenance-interval extension, and lifecycle or circularity indicators such as avoided replacement, reduced material use, downtime reduction, or repair-cycle extension. At present, the reviewed literature provides limited directly comparable numerical data on

cost, downtime, and recoatability for HP components; this absence should be treated as a qualification gap rather than hidden behind qualitative claims of circularity.

Practical CR selection must explicitly consider whether the route can be applied during a planned outage, whether it requires transport of the component to a workshop, whether post-machining is extensive, whether future removal or recoating is feasible, and whether inspection access is sufficient. TS and sealed TS are generally attractive for broad areas because they combine moderate heat input, scalable coverage, and relatively manageable finishing. LC is more justified when section loss requires material build-up, but its downtime burden may increase because of excavation, local thermal management, dilution control, machining, and inspection. CS is attractive for substrate-sensitive regions and repeated interventions, although its final durability in severe HT exposure still requires stronger validation. Chemical treatments and sealants are economically meaningful when they extend the life of a mechanically resistant primary layer, but they should not be counted as substitutes for structural rebuilding.

From a CR perspective, the preferred option is not necessarily the most wear-resistant coating, but the route that delivers sufficient durability with the lowest overall intervention burden. Refurbishment extends service life, avoids premature replacement of large cast or forged parts, and can reduce material demand and downtime-related losses [8,91]. However, these benefits depend on whether the selected protection system is repairable, inspectable, recoatable, and compatible with future maintenance cycles.

Therefore, circularity changes the basis of comparison between protection routes. Laboratory mass loss remains important, but it is insufficient on its own because it does not capture repair logistics, future maintenance flexibility, material criticality, inspection effort, or the practical cost of achieving a given service-life extension. This is especially relevant when comparing Co- or Ni-rich systems with Fe-based alternatives, or when deciding between a high-performance fusion repair and a lower-burden sprayed or CS-treated solution.

11.5. Decision Framework for Circular Refurbishment-Based Selection

The preceding sections lead to a practical decision sequence. First, the dominant degradation mechanism and the pre-repair damage class should be identified. Second, the required intervention depth should be defined as protection, sealing, surface reconditioning, or volumetric rebuilding. Third, the admissible thermal load and bonding mode should be matched to the substrate condition. Finally, the candidate route should be filtered through qualification evidence, inspection practicality, recoatability, downtime, and lifecycle value.

The resulting route selection logic is qualitative rather than prescriptive. HVOF/HVAF coatings are the most balanced option for broad-area protection where geometry is retained. LC is strongest when local rebuilding and metallurgical bonding are required. CS is most attractive when substrate preservation and low thermal burden dominate. Chemical sealing and densification are best used as enabling steps for porous or hybrid systems. Emerging HEA/MPEA, Fe-based, graded, and multilayer architectures are promising only when their microstructural advantages can be translated into repairable and inspectable refurbishment systems.

A compact circular-refurbishment decision matrix is provided to consolidate the route-selection logic. Table 7 summarizes the most appropriate use cases, main strengths, main risks, and the circular-refurbishment interpretation of the principal protection strategies discussed in this review. The matrix is qualitative and should not be interpreted as a universal ranking.

Table 7. CR decision matrix for selecting surface-protection strategies for HP components.

Strategy	Best Refurbishment Fit	Main Qualification Focus	CR Interpretation
HVOF/HVAF TS	Large-area cavitation/slurry protection where geometry is mostly retained	Porosity, splat boundaries, adhesion, residual stress, finishing roughness, and sealing, if needed. Practical qualification gate: proceed only if porosity, adhesion/cohesion strength, roughness after finishing, and post-exposure crack paths meet stated thresholds; reported dense HVOF benchmarks include porosity <2% and bond strength >70 MPa [58]	Balanced mature option when durability, downtime, cost, and recoatability must be combined
APS/arc spray/sealed spray systems	Secondary, barrier, corrosion mitigation, or auxiliary protection where severe runner cavitation is not the only requirement	Porosity, sealing penetration, wet adhesion, and suitability for the specific component zone	Useful as enabling or secondary protection, especially in sealed or hybrid systems
LC/local rebuilding	Deep craters, section loss, crack excavation zones, or contour recovery requiring metallurgical bonding	Dilution, HAZ, residual stress, cracking, distortion, machining allowance, and inspection. Practical qualification gate: proceed only if crack-free or acceptably repaired surface condition, controlled dilution/HAZ, restored geometry, retained rebuild thickness, final roughness, and inspection criteria are documented	Best when replacement is avoided, and geometry restoration justifies a higher intervention burden
CS	Thermally sensitive substrates, localized low-heat restoration, or substrate-preserving hybrid chains	Cohesion, porosity, residual stress, adhesion after immersion, finishing, and galvanic compatibility. Practical qualification gate: proceed only if adhesion/cohesion, interparticle bonding, porosity, retained thickness, post-finishing surface condition, and recoatability are reported	High circular potential where repeated repair and low collateral damage are priorities
Chemical seal-ing/densification	Auxiliary treatment for porous TS or hybrid systems exposed to wet corrosion and fluid ingress	Sealant penetration, compatibility, adhesion retention, and durability under cavitation/slurry exposure. Practical qualification gate: proceed only as an auxiliary route when reduction in open/connected porosity, corrosion-current or impedance improvement, adhesion retention after immersion, and compatibility with the primary coating are reported	Low-burden route for extending the durability of existing protection layers
Emerging HEA/MPEA, Fe-based, graded, or multilayer systems	Future high-performance or lower-criticality systems requiring architecture control	Manufacturability, mixed-mode testing, interface stability, inspection, and repairability	Promising only if novelty is converted into repairable, lifecycle-efficient systems

Table 7. Cont.

Strategy	Best Refurbishment Fit	Main Qualification Focus	CR Interpretation
Hybrid process chains	Complex damage states require removal, rebuilding, protection, sealing, finishing, and inspection	Compatibility of interfaces, thermal histories, sealants, residual stresses, and rework routes. Practical qualification gate: proceed only if each interface is qualified separately, including porosity/crack fraction, adhesion retention, final roughness, thermal history, and inspection access	Most aligned with CR when designed around reworkability and lifecycle evidence

11.6. Engineering Application of the Refurbishment Decision Framework

The decision framework should be read as a sequence of engineering gates rather than as an automatic ranking of coating families. In practice, the same material system may be suitable or unsuitable depending on component geometry, inspection access, admissible heat input, preparation depth, post-machining burden, outage duration, and the possibility of future removal or recoating.

For a Francis or Kaplan runner passage, guide vane, stay vane, or wear-ring surface that is roughened or pitted but still dimensionally stable, a dense HVOF/HVAF or sealed TS route may be practical because it can cover broad areas with moderate thermal input. The engineering decision then depends on accessibility for blasting and spraying, masking of hydraulic profiles, porosity and adhesion acceptance, finishing to recover roughness, and whether the work can be completed during a planned outage. For Pelton buckets, nozzles, needles, or splitter/brim regions affected by sediment cutting and local profile loss, field case studies show that component location and local flow acceleration strongly control damage severity; shallow damage may justify a protective sprayed or sealed route, whereas profile loss or cratered regions require excavation, LC/TC/hardfacing, machining, and renewed inspection [96–99].

The framework is therefore most useful when it forces the reviewer or engineer to state the practical constraint that governs route selection. LC or hardfacing is stronger for local rebuilding but introduces HAZ, dilution, residual-stress, crack, and machining risks. CS is attractive for thermally sensitive or repeatedly repaired regions because it avoids a fusion thermal cycle, but its HP maturity is still lower than conventional TS or LC, and it requires verification of line-of-sight deposition, cohesion, adhesion after immersion, galvanic compatibility, and final finishing [34,48,49,77,93]. Emerging HEA/MPEA and Fe-based amorphous coatings provide valuable laboratory evidence, but their field use should remain conditional on mixed-mode validation, inspection access, recoatability, feedstock availability, and cost per service-life extension [46,74–76,94,95,100] (Table 8).

Table 8. Engineering application scenarios for the refurbishment decision framework.

Maturity/Limitation	Engineering Gates Before Selection	Candidate Route Family	Dominant Engineering Constraint	Scenario/Component Family
Relatively mature; performance still depends on preparation, defect population, and field-specific sediment/corrosion exposure	Confirm damage class, remove unstable surface layers, verify roughness, porosity, adhesion, thickness, and final hydraulic roughness	HVOF/HVAF, sealed TS, or hybrid TS + sealing	Large-area access, line-of-sight deposition, profile preservation, coating finishing, and outage duration	Francis/Kaplan runner passages, blades, guide or stay vanes with roughness, pits, and retained geometry

Table 8. Cont.

Maturity/Limitation	Engineering Gates Before Selection	Candidate Route Family	Dominant Engineering Constraint	Scenario/Component Family
Field erosion cases support component-level relevance, but coating-specific long-term repair data remain limited	Use field damage mapping, assess material removal depth, plan post-machining, and confirm non-destructive testing access after repair	TS/sealed TS for shallow protection; LC/TC/hardfacing when contour recovery or material build-up is required	Profile accuracy, local accessibility, particle-impact severity, and repair downtime	Pelton buckets, splitter/brim zones, nozzles, and needles with sediment cutting or local profile loss
Engineering credible where rebuilding is required; higher thermal and post-processing burden than TS/CS	Control HAZ, dilution, residual stress, crack susceptibility, machining allowance, and final inspection criteria	Excavation + LC/TC/hardfacing + machining; possible final TS/sealing if surface protection is still required	Removal of unstable material and restoration of load-bearing geometry	Deep cavitation craters, crack networks, section-loss zones, wear rings, or labyrinth regions
Promising but less field-mature for severe HT service; requires component-scale validation	Verify line-of-sight, particle bonding, cohesion, adhesion after immersion, galvanic compatibility, and surface finishing	CS followed by finishing, sealing, or a harder top layer where needed	Avoiding distortion, avoiding new HAZ formation, and preserving previous repair zones	Thermally sensitive regions or repeated small local repairs
Useful as auxiliary barrier/sealing routes; not standalone severe cavitation/slurry solutions for runners	Confirm surface cleanliness, adhesion, water uptake, defect connectivity, and compatibility with planned inspection/recoat cycles	Organic barriers, ceramic-organic systems, chemical sealing, passivation, or sealed TS	Barrier continuity, substrate cleanliness, moisture control, and ease of future recoat	Auxiliary water-exposed structures, intakes, gates, or lower-severity corrosion/erosion zones

12. Research Gaps, Qualification Needs, and Future Directions

Future work should move beyond isolated coating performance studies toward evidence that links durability, interface stability, manufacturing feasibility, inspection, and lifecycle effects. The reviewed evidence is sufficient to support a practical route selection logic, but it also shows that HP refurbishment still lacks qualification protocols capable of connecting coupon-scale testing to field-relevant service decisions.

12.1. Standardized Mixed-Mode Testing Under Hydropower-Relevant Severity

Test comparability remains limited because cavitation, slurry erosion, corrosion, and mixed-mode exposure are not reported with uniform severity descriptors, durations, and post-test characterization depth. Many studies still isolate one mechanism at a time, even though HT service is strongly synergistic [9,24]. Future protocols should report water chemistry, sediment size and concentration, impact velocity or angle where relevant, exposure duration, roughness evolution, and post-test crack or delamination paths [25].

12.2. Weak Linkage Between Laboratory Tests and Field Life

The 2026 lifetime review shows that residual-life analysis for HP plants remains underdeveloped and extends beyond accelerated material testing [7]. Surface-protection studies should therefore connect laboratory performance indicators with inspection intervals, operating histories, off-design and transient loading, and remaining-useful-life models so that experimental improvements can inform maintenance decisions.

12.3. Need for Substrate-Aware Repair Design

A major methodological gap is the tendency to evaluate coatings as if all substrates and pre-damage states were equivalent. Refurbishment studies should explicitly encode alloy grade, heat-treatment state, previous service damage, excavation depth, preparation route, and allowable thermal window. The relevant question is not only which coating performs best, but which route is most robust for a specific damaged substrate condition.

12.4. Hybrid Routes and Circular Design as a Priority Frontier

Hybrid routes remain a priority research frontier because their additional interfaces, thermal histories, and post-processing steps require sequence-specific qualification. Future work should connect hybrid-route performance with recoatability, material removal, waste generation, feedstock criticality, downtime, and cost per lifetime extension [8,91].

12.5. Digital and Predictive Qualification

Finally, future qualification should integrate inspection data, erosion monitoring, and predictive maintenance logic. The Pelton review highlights the importance of real-time monitoring and maintenance records, while the lifetime review emphasizes the need for more complete residual-life calculations [7,12]. Bringing these strands together could enable inspection-driven refurbishment intervals and more defensible route selection for components subjected to increasingly variable HP operation.

13. Discussion

The review shows that surface protection should be treated as a refurbishment technology rather than as an isolated maintenance add-on. Its effectiveness depends on how well the service environment, substrate state, surface preparation, coating or rebuild route, post-processing, inspection, and lifecycle objectives are connected into a coherent repair chain.

13.1. Laboratory-to-Field Transferability

A critical transferability issue is that most coating and surface-treatment studies provide mechanism evidence rather than direct field-life evidence. Laboratory ultrasonic cavitation, cavitating-jet, slurry, corrosion, or adhesion tests are valuable because they allow controlled ranking of materials and interfaces, but their results should not be interpreted as direct predictions of HT lifetime unless the test conditions are connected to the actual refurbishment context [83,88–90]. This limitation is especially important because real HT components combine curved geometry, variable hydraulic loading, sediment impact, corrosion chemistry, previous service damage, and access constraints that are not reproduced by simple coupon tests [9,24,25,31].

The transferability gap can be divided into five practical levels. First, the loading mode differs: ultrasonic cavitation tests impose a controlled acoustic field, whereas HT damage is generated by flow-induced cavitation, pressure pulsation, sediment impact, corrosion-assisted attack, and transient operation [9,24,88,89]. Second, the scale differs: flat coupons do not reproduce runner-blade curvature, leading-edge geometry, local thickness variations, weld transitions, or masking and finishing constraints. Third, the substrate condition differs: real refurbished parts may contain pits, strain-hardened layers, oxide residues, embedded particles, cracks, and previous repairs [31,33,42]. Fourth, process implementation differs because deposition on large components changes heat flow, coating-thickness uniformity, roughness control, residual stresses, and post-machining effort. Fifth, qualification differs because mass loss alone does not demonstrate field suitability; adhesion/cohesion strength, porosity and crack connectivity, roughness retention, residual

stress-sensitive evidence, non-destructive inspection where applicable, and recoatability must be evaluated together [41,63,83,84].

Therefore, positive laboratory results should be interpreted as necessary but not sufficient evidence for HP refurbishment. A coating that performs well in an ultrasonic cavitation test may still fail in service if its interface is sensitive to curved-surface preparation, if open porosity enables electrolyte ingress, if finishing creates stress concentrators, or if the repaired region cannot be inspected and recoated during future maintenance cycles. Conversely, a route with moderate laboratory mass-loss performance may be more attractive for CR when it offers lower thermal burden, easier in-situ application, predictable inspection, and repeatable recoatability.

13.2. Hardness, Toughness, Defects, and Interface-Controlled Failure

The evidence base also broadens the argument that hardness alone is insufficient for route selection. In cavitation and slurry environments, material removal is controlled by cyclic impact, local plastic deformation, crack nucleation, crack propagation, and defect-assisted spallation rather than by indentation resistance alone [33,42,85]. Studies on stainless steels further show that cavitation response depends on strain hardening, ductility, phase stability, and the ability to delay crack growth [33,45]. In laser-remelted or laser-clad systems, residual stress, dilution, HAZ behavior, and cracking susceptibility can override a simple hardness-based ranking [35,46,74].

For sprayed coatings, the same principle applies at the coating-architecture level. A hard coating may perform poorly if pores, oxides, weak splat boundaries, or connected defects provide preferential sites for crack initiation and fluid ingress [63,84]. Interfacial quality is equally important, because weak coating/substrate adhesion or cohesive failure inside the coating can control failure even when the coating material itself is hard [41]. Residual stress state also affects cavitation resistance, as shown for high-kinetic HVOF/HVAF WC-CoCr coatings [55]. HT-relevant TS studies and post-treatment studies further indicate that cavitation or slurry performance depends on coating density, cohesion, post-treatment condition, and defect control, not on hardness alone [64,68,69]. Therefore, hardness should be treated as only one screening descriptor within a broader qualification set that includes toughness or fracture resistance, porosity/crack fraction, residual stress-sensitive evidence, adhesion/cohesion strength, roughness evolution, and post-exposure failure mode.

13.3. Implications for Refurbishment Route Selection

The practical implication is that route selection should begin with the damaged component rather than with the coating catalogue. The proposed framework combines damage mechanism, substrate condition, admissible process window, qualification evidence, and lifecycle value so that service suitability, repair practicality, and long-term CR value are evaluated together.

14. Conclusions

Advanced surface protection strategies for refurbished HP components should be selected through a refurbishment-oriented logic rather than by coating hardness, nominal composition, or isolated laboratory performance alone. The critical variables are the dominant damage mechanism, the pre-repair substrate condition, the admissible thermal input, the required build-up thickness, the coating/interface defect state, and the expected CR value.

TS remains the most mature route for broad-area protection when dense coatings, controlled porosity, adequate adhesion, and feasible finishing can be achieved. LC and related TC routes are more appropriate when local rebuilding, contour recovery, and metal-

lurgical bonding are required, but their advantages must be balanced against dilution, HAZ formation, residual stress, cracking risk, and machining burden. CS offers a promising low-heat-input alternative for substrate-sensitive repairs, while chemical sealing, passivation, and densification are best considered as enabling steps that improve interface stability and reduce fluid ingress rather than as standalone solutions for severe HP loading.

The review also shows that emerging HEA, MPEA, Fe-based amorphous, graded, and multilayer systems should be judged by their repairability, inspectability, interface stability, and lifecycle performance, not only by material novelty. Their strongest role is likely to be in hybrid refurbishment architectures where rebuilding, protection, sealing, finishing, and inspection are combined in a route-specific sequence.

The main unresolved challenge is the lack of HP-relevant qualification protocols that connect laboratory cavitation, slurry, corrosion, and mixed-mode testing with substrate state, inspection criteria, remaining useful life, and circular-economy indicators. Future progress should therefore focus on hybrid refurbishment chains, combined cavitation-slurry-corrosion testing, long-term field validation, inspection-based qualification, and lifecycle-based decision criteria for industrial-scale CR of HP components.

Author Contributions: Conceptualization, G.S.S. and L.S.; methodology, L.S.; investigation, G.D.L. and S.F.; writing—original draft preparation, L.S.; writing—review and editing, G.S.S. and L.S.; visualization, G.D.L. and S.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Horizon Europe project “Revolutionary Refurbishment for an Efficient and Eco-Friendly Hydropower—REVHYDRO”, Grant Agreement ID 101172857, funded under the “Climate, Energy and Mobility” cluster, Funding Scheme HORIZON-CL5-2024-D3-01-07, HORIZON Research and Innovation Actions.

Data Availability Statement: The original contributions presented in this study are included in the article’s materials. Further inquiries can be directed to the corresponding authors.

Acknowledgments: During the preparation of this manuscript, the authors used Microsoft Copilot and Grammarly for language editing (grammar/readability). The authors reviewed and edited the output and take full responsibility for the content of this publication.

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

Abbreviations

APS	atmospheric plasma spray
CE	cavitation erosion
CR	circular refurbishment
CS	cold spray
HAZ	heat-affected zone
HEA	high-entropy alloy
HP	hydropower
HT	hydraulic turbine
HVOF	high-velocity oxy-fuel
HVAF	high-velocity air-fuel
LC	laser cladding
MPEA	multi-principal-element alloy
SMA	shape-memory alloy
TC	thermal cladding
TS	thermal spray

References

- Blume-Werry, E.; Everts, M. Hydropower. In *The Palgrave Handbook of International Energy Economics*; Springer: Cham, Switzerland, 2022; pp. 145–156.
- Wasti, A.; Ray, P.; Wi, S.; Folch, C.; Ubierna, M.; Karki, P. Climate change and the hydropower sector: A global review. *Wiley Interdiscip. Rev. Clim. Change* **2022**, *13*, e757. [\[CrossRef\]](#)
- Gulliver, J.S.; Arndt, R.E. *Hydropower Engineering Handbook*; McGraw-Hill: New York, NY, USA, 1991.
- Pal, N.; Khan, F.A. Hydropower Technology. In *Sustainable Fuel Technologies Handbook*; Dutta, S., Hussain, C.M., Eds.; Academic Press: San Diego, CA, USA, 2021; pp. 91–120.
- Vagnoni, E.; Gezer, D.; Anagnostopoulos, I.; Cavazzini, G.; Doujak, E.; Hočevár, M.; Rudolf, P. The new role of sustainable hydropower in flexible energy systems and its technical evolution through innovation and digitalization. *Renew. Energy* **2024**, *230*, 120832. [\[CrossRef\]](#)
- Görtz, J.; Aouad, M.; Wieprecht, S.; Terheiden, K. Assessment of pumped hydropower energy storage potential along rivers and shorelines. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112027. [\[CrossRef\]](#)
- Nobilo, M.; Salehi, S.; Nilsson, H. Lifetime analysis of hydro turbines with focus on fatigue damage in a renewable energy system—A review. *Renew. Sustain. Energy Rev.* **2026**, *228*, 116578. [\[CrossRef\]](#)
- Lakatos, E.S.; Ferenci, S.; Albu, R.M.; Posa, M.-V.; Munteanu, R.A.; Szabó, L.; Cioca, L.-I. Multi-criteria LCA framework for sustainable hydropower refurbishment design. *Energies* **2026**, *19*, 1390. [\[CrossRef\]](#)
- Wang, C.; Tan, L.; Chen, M.; Fan, H.; Liu, D. A review on synergy of cavitation and sediment erosion in hydraulic machinery. *Front. Energy Res.* **2022**, *10*, 1047984. [\[CrossRef\]](#)
- Shrestha, R.; Gurung, P.; Chitrakar, S.; Thapa, B.; Neopane, H.P.; Guo, Z.; Qian, Z. Review on experimental investigation of sediment erosion in hydraulic turbines. *Front. Mech. Eng.* **2024**, *10*, 1526120. [\[CrossRef\]](#)
- Singh, R.; Tiwari, S.A.; Mishra, S.K. Cavitation erosion in hydraulic turbine components and mitigation by coatings: Current status and future needs. *J. Mater. Eng. Perform.* **2012**, *21*, 1539–1551. [\[CrossRef\]](#)
- Ge, X.; Sun, J.; Chu, D.; Liu, J.; Zhou, Y.; Zhang, H.; Zhang, L.; Chen, H.; Kan, K.; Binama, M. Sediment erosion on Pelton turbines: A review. *Chin. J. Mech. Eng.* **2023**, *36*, 64. [\[CrossRef\]](#)
- Raqib Qaderi, A.; Chitrakar, S.; Prasad Neopane, H.; Gunnar Dahlhaug, O. Comprehensive Review of Sediment Erosion Mechanisms and Their Impact on Francis Turbines. In *IOP Conference Series: Earth and Environmental Science*; Purpose-Led: Melville, NY, USA, 2025; p. 012009. [\[CrossRef\]](#)
- Baral, B.; Kharel, B.; Dawadi, A.; Timsina, S.; Bhattarai, S.; Joshi, R. Sustainable manufacturing practices in the hydropower industry: A review. In *IOP Conference Series: Earth and Environmental Science*; Purpose-Led: Melville, NY, USA, 2024; p. 012017. [\[CrossRef\]](#)
- Lakatos, G.D.; Albu, R.M.; Rhazzali, A.L.; Ferenci, S.; Cioca, L.I.; Munteanu, R.A.; Szabó, L. The role of hydraulic turbines in the energy transition: A systematic review of methods for evaluating and optimizing hydropower plant operation. *Processes* **2026**, *14*, 841. [\[CrossRef\]](#)
- Vaz, R.F.; León, M.; Silvello, A.; Garcia Cano, I. Coatings for Hydro Turbine Applications: A Materials Perspective. *Metals* **2026**, *16*, 406. [\[CrossRef\]](#)
- Singh, H.; Kumar, M.; Kumar, S.; Singh, S. Corrosion, Wear, Erosion, and Abrasion in Hydropower Plants by Thermal Spray Coatings. In *Thermal Spray Coatings: Materials, Techniques & Applications*; Kumar, S., Khanna, V., Eds.; Bentham Science Publishers: Sharjah, United Arab Emirates, 2024; pp. 127–158.
- Lakkannavar, V.; Yogesha, K.; Prasad, C.D.; Mruthunjaya, M.; Suresh, R. A review on tribological and corrosion behaviour of thermal spray coatings. *J. Inst. Eng. (India) Ser. D* **2025**, *106*, 753–769. [\[CrossRef\]](#)
- Singh, H. Challenges of Corrosion, Wear, Erosion, and Abrasion in Hydropower Plants: Materials, Modeling, and Mitigation Strategies. *Eng. Trans.* **2026**. [\[CrossRef\]](#)
- Wu, P.; Sun, S.; Guo, P.; Nan, H.; Wang, T.; Zheng, X. Cavitation erosion characteristics and mechanisms of hydraulic turbine substrates and their coatings. *Ultrason. Sonochem.* **2025**, 107732. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kashyap, T.; Thakur, R.; Ngo, G.H.; Lee, D.; Fekete, G.; Kumar, R.; Singh, T. Silt erosion and cavitation impact on hydraulic turbines performance: An in-depth analysis and preventative strategies. *Heliyon* **2024**, *10*, e28998. [\[CrossRef\]](#) [\[PubMed\]](#)
- Shrivastava, N.; Rai, A.K. Hydro-abrasive erosion in Pelton turbines: Comprehensive review and future outlook. *Renew. Sustain. Energy Rev.* **2025**, *207*, 114957. [\[CrossRef\]](#)
- Rai, A.K.; Kumar, A.; Staubli, T. Effect of concentration and size of sediments on hydro-abrasive erosion of Pelton turbine. *Renew. Energy* **2020**, *145*, 893–902. [\[CrossRef\]](#)
- Kumar, P.; Singal, S.; Gohil, P.P. A technical review on combined effect of cavitation and silt erosion on Francis turbine. *Renew. Sustain. Energy Rev.* **2024**, *190*, 114096. [\[CrossRef\]](#)
- Noon, A.A.; Kim, M.-H. Sediment and cavitation erosion in Francis turbines—Review of latest experimental and numerical techniques. *Energies* **2021**, *14*, 1516. [\[CrossRef\]](#)

26. Zhao, X.; Peng, Y.; Yang, J.; Ren, M.; Liu, X. Experimental analysis of the effect of wear factors on guide vane of hydraulic turbine. *Machines* **2022**, *10*, 264. [\[CrossRef\]](#)
27. Liu, X.; Luo, Y.; Wang, Z. A review on fatigue damage mechanism in hydro turbines. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1–14. [\[CrossRef\]](#)
28. Kumar, R.; Bhandari, D.; Goyal, K. *Slurry Erosion Behaviour of HVOF Sprayed Coatings on Hydro Turbine Steel: A Review*; IOP Publishing: Bristol, UK, 2021; Volume 1033, p. 012064.
29. Thapa, B.S.; Dahlhaug, O.G.; Thapa, B. Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine. *Renew. Sustain. Energy Rev.* **2015**, *49*, 1100–1113. [\[CrossRef\]](#)
30. Koirala, R.; Thapa, B.; Neopane, H.P.; Zhu, B. A review on flow and sediment erosion in guide vanes of Francis turbines. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1054–1065. [\[CrossRef\]](#)
31. Dorji, U.; Ghomashchi, R. Hydro turbine failure mechanisms: An overview. *Eng. Fail. Anal.* **2014**, *44*, 136–147. [\[CrossRef\]](#)
32. Khalid Mohammed Ridha, W.; Reza Kashyzadeh, K.; Ghorbani, S. Common failures in hydraulic Kaplan turbine blades and practical solutions. *Materials* **2023**, *16*, 3303. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Tian, Y.; Zhao, H.; Yang, R.; Liu, X.; Chen, X.; Qin, J.; McDonald, A.; Li, H. In-situ SEM investigation on stress-induced microstructure evolution of austenitic stainless steels subjected to cavitation erosion and cavitation erosion-corrosion. *Mater. Des.* **2022**, *213*, 110314. [\[CrossRef\]](#)
34. Jafari, R.; Pero, R.; Helmi, E.; Zohrevand, M.; Gundgire, T.; Honkanen, M.; Vippola, M.; Koivuluoto, H. Improved structural integrity of cold-sprayed aluminum alloy-quasicrystal composite coatings assessed by cavitation erosion testing. *Appl. Surf. Sci. Adv.* **2026**, *31*, 100924. [\[CrossRef\]](#)
35. Liu, G.-l.; Zhang, Y.; Lian, Z.-p.; Xu, J.-l.; Wang, J.; Zhang, M.-t.; Xue, W.-c.; Liu, H.-x.; Zhou, J.-z. Cavitation erosion performance and phase transformation strengthening behavior of laser clad iron-based shape memory alloy coatings. *Mater. Today Commun.* **2024**, *41*, 110184. [\[CrossRef\]](#)
36. Kumar, V.; Singh, J. Assessment of Slurry Erosion in Pumps and Hydraulic Turbines. In *Slurry Erosion. Flow Phenomenon, Complexities, and Protection Methods*; Singh, J., Kumar, S., Eds.; CRC Press: Boca Raton, FL, USA, 2026; pp. 80–102.
37. Wang, Y.-Y.; Li, C.-J.; Ohmori, A. Influence of substrate roughness on the bonding mechanisms of high velocity oxy-fuel sprayed coatings. *Thin Solid Films* **2005**, *485*, 141–147. [\[CrossRef\]](#)
38. Staia, M.; Ramos, E.; Carrasquero, A.; Roman, A.; Lesage, J.; Chicot, D.; Mesmacque, G. Effect of substrate roughness induced by grit blasting upon adhesion of WC-17% Co thermal sprayed coatings. *Thin Solid Films* **2000**, *377*, 657–664. [\[CrossRef\]](#)
39. Tawade, P.; Shembale, S.; Hussain, S.; Sabiruddin, K. Effects of different grit blasting environments on the prepared steel surface. *J. Therm. Spray Technol.* **2023**, *32*, 1535–1553. [\[CrossRef\]](#)
40. Balić, E.E.; Hadad, M.; Bandyopadhyay, P.P.; Michler, J. Fundamentals of adhesion of thermal spray coatings: Adhesion of single splats. *Acta Mater.* **2009**, *57*, 5921–5926. [\[CrossRef\]](#)
41. Shinde, S.; Sampath, S. A critical analysis of the tensile adhesion test for thermally sprayed coatings. *J. Therm. Spray Technol.* **2022**, *31*, 2247–2279. [\[CrossRef\]](#)
42. Wang, Z.; Zhang, B. Cracking mechanism of CA6NM hydro turbine steel in cavitation erosion. *Tribol. Int.* **2025**, *202*, 110325. [\[CrossRef\]](#)
43. Allenstein, A.; Lepienski, C.; Buschinelli, A.d.A.; Brunatto, S. Improvement of the cavitation erosion resistance for low-temperature plasma nitrided Ca-6NM martensitic stainless steel. *Wear* **2014**, *309*, 159–165. [\[CrossRef\]](#)
44. Melvin, V. Cavitation erosion resistance of low-temperature plasma nitrided ca-6NM martensitic stainless steel. In Proceedings of the International Conference on Mathematical and Statistical Physics, Computational Science, Education, and Communication (ICMSCE '2025), Istanbul, Turkey, 11–12 July 2025; pp. 67–73. [\[CrossRef\]](#)
45. Zhao, L.; Hu, H.; Guo, X. Effect of toughness and ductility on the cavitation erosion of martensitic stainless steel. *Metals* **2023**, *13*, 154. [\[CrossRef\]](#)
46. Zhang, Z.; Yu, Y.; Chen, X.; Fu, L.; Wei, X.; Zhang, W.; Dong, Z.; Wang, M.; Wang, T.; Hui, X. Tailoring microstructure and properties of CoCrNiAlTiNb high-entropy alloy coatings via laser power control during laser cladding. *Materials* **2025**, *19*, 5. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Moridi, A.; Hassani-Gangaraj, S.M.; Guagliano, M.; Dao, M. Cold spray coating: Review of material systems and future perspectives. *Surf. Eng.* **2014**, *30*, 369–395. [\[CrossRef\]](#)
48. Luo, X.-T.; Li, C.-X.; Shang, F.-L.; Yang, G.-J.; Wang, Y.-Y.; Li, C.-J. High velocity impact induced microstructure evolution during deposition of cold spray coatings: A review. *Surf. Coat. Technol.* **2014**, *254*, 11–20. [\[CrossRef\]](#)
49. 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. [\[CrossRef\]](#)
50. Mali, M.; Siram, O.; Biswas, A.; Das, B. Application of thermally sprayed coating in hydrokinetic turbines to reduce the slurry-based erosion: A review. *Renew. Sustain. Energy Rev.* **2026**, *234*, 116922. [\[CrossRef\]](#)

51. Govande, A.R.; Chandak, A.; Sunil, B.R.; Dumpala, R. Carbide-based thermal spray coatings: A review on performance characteristics and post-treatment. *Int. J. Refract. Met. Hard Mater.* **2022**, *103*, 105772. [\[CrossRef\]](#)
52. Varis, T.; Suhonen, T.; Laakso, J.; Jokipii, M.; Vuoristo, P. Evaluation of residual stresses and their influence on cavitation erosion resistance of high kinetic HVOF and HVAF-sprayed WC-CoCr coatings. *J. Therm. Spray Technol.* **2020**, *29*, 1365–1381. [\[CrossRef\]](#)
53. Li, C.-J.; Luo, X.-T.; Yao, S.-W.; Li, G.-R.; Li, C.-X.; Yang, G.-J. The bonding formation during thermal spraying of ceramic coatings: A review. *J. Therm. Spray Technol.* **2022**, *31*, 780–817. [\[CrossRef\]](#)
54. Odhiambo, J.G.; Li, W.; Zhao, Y.; Li, C. Porosity and its significance in plasma-sprayed coatings. *Coatings* **2019**, *9*, 460. [\[CrossRef\]](#)
55. Hong, S.; Wu, Y.; Wu, J.; Zhang, Y.; Zheng, Y.; Li, J.; Lin, J. Microstructure and cavitation erosion behavior of HVOF sprayed ceramic-metal composite coatings for application in hydro-turbines. *Renew. Energy* **2021**, *164*, 1089–1099. [\[CrossRef\]](#)
56. Saldarriaga-Montoya, V.; Castillo, J.; Yomayuya-Sierra, N.; Benítez-Castro, A.; Muñoz-Castillo, J.; Rodríguez-Arévalo, S.; González-Hernández, J.; García-Moreno, A.; Muñoz-Saldaña, J. Physics-informed plume diagnostics for process-structure-property relationships in AC-HVAF thermal spray processing. *Surf. Coat. Technol.* **2026**, *535*, 133733. [\[CrossRef\]](#)
57. Faisal, N.H.; Prathuru, A.; Ahmed, R.; Rajendran, V.; Hossain, M.; Venkatachalapathy, V.; Katiyar, N.K.; Li, J.; Liu, Y.; Cai, Q. Application of thermal spray coatings in electrolyzers for hydrogen production: Advances, challenges, and opportunities. *ChemNanoMat* **2022**, *8*, e202200384. [\[CrossRef\]](#)
58. Hong, S.; Shi, X.; Lin, J.; Wu, Y.; Li, J.; Zheng, Y. Microstructure and cavitation-silt erosion behavior of two HVOF-sprayed hardfacing coatings for hydro-turbine applications. *Alex. Eng. J.* **2023**, *69*, 483–496. [\[CrossRef\]](#)
59. Prashar, G.; Vasudev, H.; Thakur, L. Performance of different coating materials against slurry erosion failure in hydrodynamic turbines: A review. *Eng. Fail. Anal.* **2020**, *115*, 104622. [\[CrossRef\]](#)
60. Singh, S.; Berndt, C.C.; Raman, R.K.S.; Singh, H.; Ang, A.S.M. Applications and developments of thermal spray coatings for the iron and steel industry. *Materials* **2023**, *16*, 516. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Kumar, S.S.; Prasad, C.D.; Hanumanthappa, H. Role of thermal spray coatings on erosion, corrosion, and oxidation in various applications: A review. *J. Bio-Tribo-Corros.* **2024**, *10*, 22. [\[CrossRef\]](#)
62. Guillon, O.; Dash, A.; Lenser, C.; Uhlenbruck, S.; Mauer, G. Tuning the microstructure and thickness of ceramic layers with advanced coating technologies using zirconia as an example. *Adv. Eng. Mater.* **2020**, *22*, 2000529. [\[CrossRef\]](#)
63. Lee, H.-S.; Singh, J.K.; Ismail, M.A. An effective and novel pore sealing agent to enhance the corrosion resistance performance of Al coating in artificial ocean water. *Sci. Rep.* **2017**, *7*, 41935. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Boronenkov, V.; Korobov, Y. *Fundamentals of Arc Spraying. Physical and Chemical Regularities*; Springer: Cham, Switzerland, 2016.
65. Newbery, A.; Grant, P.; Neiser, R. The velocity and temperature of steel droplets during electric arc spraying. *Surf. Coat. Technol.* **2005**, *195*, 91–101. [\[CrossRef\]](#)
66. Jiao, J.; Luo, Q.; Wei, X.; Wang, Y.; Shen, J. Influence of sealing treatment on the corrosion resistance of Fe-based amorphous coatings in HCl solution. *J. Alloys Compd.* **2017**, *714*, 356–362. [\[CrossRef\]](#)
67. Liscano, S.; Gil, L.; Staia, M.H. Effect of sealing treatment on the corrosion resistance of thermal-sprayed ceramic coatings. *Surf. Coat. Technol.* **2004**, *188*, 135–139. [\[CrossRef\]](#)
68. Zeng, Y.; Zhao, L.; Si, C.; Xu, S.; Wang, J. Effect of heat treatment on cavitation erosion and wear properties of nanostructured WC-10Co4Cr coatings. *Int. J. Refract. Met. Hard Mater.* **2025**, *135*, 107542. [\[CrossRef\]](#)
69. Babu, A.; Perumal, G.; Arora, H.; Grewal, H. Enhanced slurry and cavitation erosion resistance of deep cryogenically treated thermal spray coatings for hydroturbine applications. *Renew. Energy* **2021**, *180*, 1044–1055. [\[CrossRef\]](#)
70. Lugscheider, E.; Jakiel, P.; Messerschmidt, V.; Beckschulte, G. Subsequent sealing of thermally sprayed coatings to increase corrosion resistance. *Surf. Eng.* **1994**, *10*, 46–51. [\[CrossRef\]](#)
71. Le Thu, Q.; Nguyen, T.A.; Ly, Q.C.; Ly, P.T.; Ha, P.T.; Mai, T.D.T. Arc thermal spray NiCr20 alloy coating: Fabrication, sealant, heat treatment, wear, and corrosion resistances. *Int. J. Electrochem.* **2019**, *2019*, 8796958. [\[CrossRef\]](#)
72. Mitelea, I.; Bordeasu, I.; Cosma, D.; Buzdugan, D.; Crăciunescu, C.M.; Uțu, I.D. Assessment of corrosion and cavitation resistance of laser remelted GX40CrNiSi25-20 cast stainless steel. *Materials* **2024**, *17*, 6278. [\[CrossRef\]](#) [\[PubMed\]](#)
73. Kwok, C.; Man, H.C.; Cheng, F.; Lo, K. Developments in laser-based surface engineering processes: With particular reference to protection against cavitation erosion. *Surf. Coat. Technol.* **2016**, *291*, 189–204. [\[CrossRef\]](#)
74. Chen, X.; Wang, J.; Wu, Y.; Wei, X.; Meng, Q.; Dong, Z.; Fu, L.; Hui, X. Enhanced cavitation erosion resistance of FeCrNiTiAlNb multi-principal element alloy coatings via grain-boundary-phase engineering. *Scr. Mater.* **2025**, *269*, 116906. [\[CrossRef\]](#)
75. Bao, Y.; Guo, L.; Zhong, C.; Song, Q.; Yang, K.; Jiang, Y.; Wang, Z. Effects of WC on the cavitation erosion resistance of FeCoCrNiB0.2 high entropy alloy coating prepared by laser cladding. *Mater. Today Commun.* **2021**, *26*, 102154. [\[CrossRef\]](#)
76. Zhang, K.; Su, Z.; Xu, S.; Wu, L.; Zhang, X.; Zhou, Z.; Wang, G. Effect of efficient structural tuning on the microstructure, corrosion resistance, and wear performance of AlCoCrFeNi/AT13 composite coatings. *Tribol. Int.* **2025**, *202*, 110377. [\[CrossRef\]](#)
77. Zhang, J.; Kong, D. Effect of laser remelting on friction-wear behaviors of cold sprayed Al coatings in 3.5% NaCl solution. *Materials* **2018**, *11*, 283. [\[CrossRef\]](#) [\[PubMed\]](#)

78. Deng, W.; Hou, G.; Li, S.; Han, J.; Zhao, X.; Liu, X.; An, Y.; Zhou, H.; Chen, J. A new methodology to prepare ceramic-organic composite coatings with good cavitation erosion resistance. *Ultrason. Sonochem.* **2018**, *44*, 115–119. [[CrossRef](#)] [[PubMed](#)]
79. Wang, Y.; Gang, Y.; Su, L.; Wang, T.; Cai, Y.; Li, X.; Liu, X.; Pang, J. Research on sediment erosion and anti-wear coating materials for water-intake components of hydraulic turbines in sandy rivers. *Water* **2024**, *16*, 2764. [[CrossRef](#)]
80. Sharma, R.; Das, R.; Kumar, S. Microstructure, mechanical and tribological properties of high velocity oxy fuel thermal spray coating: A review. *Mater. Sci. Eng.* **2023**, *54*, 90–97. [[CrossRef](#)]
81. Wijewardane, S. Thermal Spray Coatings in Renewable Energy Applications. In *Future Development of Thermal Spray Coatings. Types, Designs, Manufacture and Applications*; Espallargas, N., Ed.; Woodhead Publishing: Cambridge, UK, 2015; pp. 241–257.
82. Matikainen, V.; Peregrina, S.R.; Ojala, N.; Koivuluoto, H.; Schubert, J.; Houdková, Š.; Vuoristo, P. Erosion wear performance of WC-10Co4Cr and Cr3C2-25NiCr coatings sprayed with high-velocity thermal spray processes. *Surf. Coat. Technol.* **2019**, *370*, 196–212. [[CrossRef](#)]
83. ASTM C633-24; Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings. ASTM International: West Conshohocken, PA, USA, 2024.
84. Bhosale, D.G.; Dorlikar, C.; Bhosale, A.P.; Pasare, V.; Maurya, B.; Korgaonkar, S.; Ginwal, V.; Prabhu, T.R. Performance of thermal-sprayed WC-Cr3C2-Ni coatings in slurry erosion for hydrodynamic turbines. *Tribol.-Mater. Surf. Interfaces* **2022**, *16*, 292–302. [[CrossRef](#)]
85. Krella, A.K. Degradation and protection of materials from cavitation erosion: A review. *Materials* **2023**, *16*, 2058. [[CrossRef](#)] [[PubMed](#)]
86. Sathish, M.; Radhika, N.; Saleh, B. Duplex and composite coatings: A thematic review on thermal spray techniques and applications. *Met. Mater. Int.* **2023**, *29*, 1229–1297. [[CrossRef](#)]
87. GB/T 43100-2023; Thermal Spraying—Post-Treatment and Finishing of Thermally Sprayed Coatings. Standardization Administration of China: Beiling, China, 2023.
88. ASTM G32-21; Standard Test Method for Cavitation Erosion Using Vibratory Apparatus. ASTM International: West Conshohocken, PA, USA, 2021.
89. ASTM G134-23; Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet. ASTM International: West Conshohocken, PA, USA, 2023.
90. ASTM G76-18; Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets. ASTM International: West Conshohocken, PA, USA, 2018.
91. Rhazzali, A.L.; Lakatos, E.S.; Minea, G.; Cioca, L.-I.; Barnisca, M.; Ferenci, S.; Szabó, L.; Munteanu, R.A. Measuring circular economy indicator in hydropower refurbishment. *Energies* **2025**, *18*, 5922. [[CrossRef](#)]
92. Singh, S.; Farwaha, H.S.; Kumar, R.; Ariffin, I.; Beemkumar, N.; Grewal, J.S.; Singh, I.; Bhowmik, A.; Fendzi Mbasso, W. Slurry erosion performance of WC-Co and Cr3C2-NiCr coatings on hydro turbine steel: Optimization and modelling under variable operational conditions. *Oxf. Open Mater. Sci.* **2025**, *5*, itaf008. [[CrossRef](#)]
93. Jiang, X.; Overman, N.; Smith, C.; Ross, K. Microstructure, hardness and cavitation erosion resistance of different cold spray coatings on stainless steel 316 for hydropower applications. *Mater. Today Commun.* **2020**, *25*, 101305. [[CrossRef](#)]
94. Wang, C.; Jiang, B.; Ren, J.; Song, R. Effects of spraying power on Fe-based amorphous coatings. *Surf. Eng.* **2024**, *40*, 299–309. [[CrossRef](#)]
95. Gao, G.; Lin, J.; Liu, J.; Fu, X.; Kang, M. Effect of laser remelting on the cavitation erosion behaviors of high-velocity arc-sprayed Fe-based amorphous coating in different medium. *Ultrason. Sonochem.* **2025**, *120*, 107484. [[CrossRef](#)] [[PubMed](#)]
96. Sharma, S.; Gandhi, B.K.; Pandey, L. Measurement and analysis of sediment erosion of a high head Francis turbine: A field study of Bhilangana-III hydropower plant, India. *Eng. Fail. Anal.* **2021**, *122*, 105249. [[CrossRef](#)]
97. Bajracharya, T.; Acharya, B.; Joshi, C.; Saini, R.; Dahlhaug, O. Sand erosion of Pelton turbine nozzles and buckets: A case study of Chilime Hydropower Plant. *Wear* **2008**, *264*, 177–184. [[CrossRef](#)]
98. Koirala, R.; Thapa, B.; Neopane, H.P.; Zhu, B.; Chhetry, B. Sediment erosion in guide vanes of Francis turbine: A case study of Kaligandaki Hydropower Plant, Nepal. *Wear* **2016**, *362*, 53–60. [[CrossRef](#)]
99. Cruzatty, C.; Jimenez, D.; Valencia, E.; Zambrano, I.; Mora, C.; Luo, X.; Cando, E. A case study: Sediment erosion in Francis turbines operated at the San Francisco hydropower plant in Ecuador. *Energies* **2021**, *15*, 8. [[CrossRef](#)]
100. Zhao, T.; Wang, L.; Zhang, S.; Zhang, C.; Sun, X.; Chen, H.; Bai, X.; Wu, C. Effect of synergistic cavitation erosion-corrosion on cavitation damage of CoCrFeNiMn high entropy alloy layer by laser cladding. *Surf. Coat. Technol.* **2023**, *472*, 129940. [[CrossRef](#)]

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.