

Surface texturing for particle erosion and cavitation erosion resistance enhancement: A comprehensive review

Ning Wang^a, Ping Chen^{a,b,*}, Xueqi Ye^a, Yi Zhang^a, Weixu Yang^a

^a School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China

^b Shunde Innovation School, University of Science and Technology Beijing, Foshan 528399, China

Corresponding author. E-mail: chenp@ustb.edu.cn (P. Chen)

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Abstract

Particle erosion and cavitation erosion pose persistent challenges to engineering surfaces across diverse sectors such as energy, aviation, marine, and manufacturing, frequently causing severe material degradation, operational inefficiencies, and economic losses. Surface texturing has emerged as a highly effective protection strategy, capable of significantly enhancing particle erosion and cavitation erosion resistance through near-wall flow modulation, particle impact redistribution, and mitigation of bubble collapse-induced pressure spikes. This review presents a comprehensive synthesis of recent advances in surface texturing technologies aimed at enhancing particle erosion and cavitation erosion resistance. The fundamental mechanisms governing solid particle erosion and cavitation erosion are first elucidated, followed by

a comprehensive summary of theoretical frameworks for erosion–cavitation synergy and an in-depth exposition of theoretical modeling approaches for textured surfaces. Diverse surface texturing methods are systematically reviewed, with a focus on laser surface texturing, additive manufacturing-enabled micro/nano-structuring, and mechanical or hybrid surface treatments. The effects of texture geometry, scale, and arrangement on hydrodynamic flow, impact angle distribution, and stress modulation are analyzed in conjunction with substrate mechanical properties such as hardness, toughness, and residual stress. Complementary coating techniques and biomimetic morphology-material coupling strategies that synergistically enhance wear resistance and wettability are also discussed. Experimental characterization methodologies and numerical modeling approaches for performance evaluation are presented. Finally, future research directions are outlined, advocating integrated surface engineering solutions that combine texture design, material modification, and advanced modeling to optimize multi-functional resistance under complex erosive conditions.

Keywords:

Surface texturing, Particle erosion resistance, Cavitation erosion resistance, Computational fluid dynamics, Laser micro/nano-structuring

1. Introduction

Solid particle erosion is a prevalent phenomenon where material surfaces sustain damage due to collisions with solid particles, leading to mass flaws through energy exchange between impacting particles and surfaces [1-5]. The material removal process depends on multiple parameters, including particle size, shape, impact velocity, impact angle, and material properties such as hardness and fracture toughness [6,7]. For ductile materials, this energy results in plastic deformation or direct material removal, while brittle materials experience crack initiation and propagation, leading to material removal [8,9]. Angular particles cause more severe damage than spherical ones by inducing cutting and stress concentration, and harder particles, larger particle sizes (up to a limit), and higher impact velocities (with an exponential influence due to kinetic energy) all increase erosion rates [10,11]. Material hardness enhances erosion resistance by resisting plastic deformation, whereas lower fracture toughness increases brittleness and erosion rates, with surface morphology further influencing these properties [12,13]. Surface morphology plays a critical role in mitigating solid particle erosion [14]. The micro-textures on the surfaces of animals and plants in nature exhibit excellent erosion resistance (as shown in Figure 1), such as grooves, pits, and bumps that can alter particle impact velocity, trajectory, and relative impact angle [15,16]. For instance, V-shaped grooves reduce erosion by diversifying local impingement angles; at low angles, cutting dominates erosion, while plastic deformation and fracture become more significant at higher angles [17]. Multiple particle impacts and air swirls within grooves have negligible effects compared to the angle diversification mechanism. Morphology-material coupled biomimetic surfaces, combining features like grooves/bumps with a hard surface layer and soft interior, further enhance erosion resistance through synergistic effects [18].

Cavitation is a hydrodynamic phenomenon in which vapor bubbles form due to a local pressure drop in a liquid; it is not inherently detrimental. For example, the inability of pressure to decrease indefinitely within a cavitation region is precisely the

mechanism that enhances the load-carrying capacity of textured surfaces. Cavitation erosion, by contrast, refers to the material damage caused by the collapse of such bubbles near a solid surface. These two processes are fundamentally distinct. Cavitation erosion occurs when vapor bubbles collapse near solid surfaces, generating high-pressure microjets and impact pressures that cause plastic deformation, strain hardening, and fatigue crack extension [19-23]. Key mechanisms include micro-jet impacts and collapse pressure waves [24,25], with damage initiating preferentially at interfaces and grain boundaries due to uneven strain distributions [26]. Bubble dynamics, modeled by a modified Rayleigh-Plesset equation, show shock wave pressure depends on ultrasonic amplitude, with supersonic bubble wall motion generating strong shocks [27-29]. Hydrodynamic cavitation arises from flow-induced pressure drops forming large cavities, while acoustic cavitation involves ultrasonic waves driving bubble oscillations [30]. Surface texturing mitigates cavitation erosion: groove structures form water cushions, redirect microjet trajectories, and reduce stress concentration, with groove width/spacing ratio influencing performance [31].

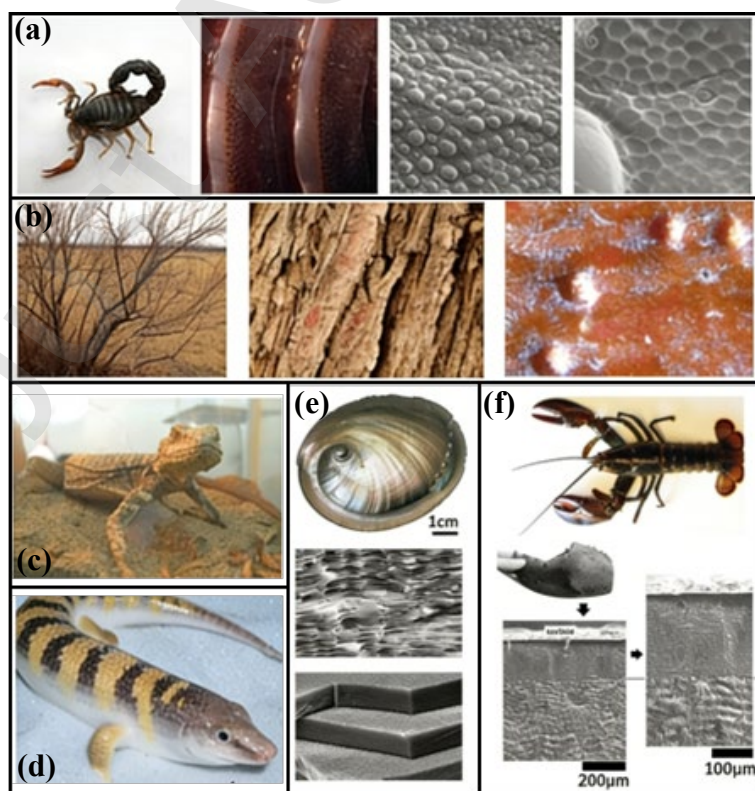


Figure 1. Micro-textures in nature [15]: (a) *Androctonus australis*, (b) *tamarix chinensis*, (c) *laudakin stoliczkana*, (d) *scincus scincus*, (e) *haliotis laevigata*, and (f) *homarus americanus*.

The synergistic interaction between erosion and cavitation is a critical but still unexplored dimension in surface damage research. A key manifestation of this synergy is the acceleration of solid particles by cavitation bubble collapse-induced microjets, where the imparted particle velocity is governed by particle mass, bubble radius, and relative spatial position [32-36]. Although solid particle erosion and cavitation erosion differ fundamentally in their damage mechanisms—the former being dominated by sequential impact-induced plastic deformation or brittle fracture, and the latter by repetitive shock waves and microjet impingement from bubble collapse—they share substantial intrinsic connections in the context of surface texturing [37,38]. From a unified physical process perspective, both phenomena fundamentally involve the interaction between a material surface and an external aggressive medium (solid particles or collapsing cavitation bubbles), wherein surface textures serve as a common regulatory factor by modulating local hydrodynamic characteristics, near-surface stress distributions, and energy dissipation pathways. Critically, these two damage modes are not merely superposed but mutually reinforced: cavitation-generated microjets can pre-damage the surface, thereby lowering the threshold for subsequent particle erosion, while surface roughness introduced by particle impacts can, in turn, nucleate additional cavitation sites. A thorough investigation of the synergistic interaction can facilitate a more comprehensive understanding of how surface texturing mitigates damage, thereby providing a systematic theoretical basis for the rational design of multifunctional anti-damage surface architectures.

This review comprehensively summarizes recent advancements in surface texturing technologies aimed at enhancing particle erosion and cavitation erosion resistance. It elucidates the fundamental mechanisms governing solid particle erosion and cavitation erosion, with particular emphasis on the roles of material properties, particle dynamics, and fluid–bubble interactions, and synthesizes theoretical frameworks that integrate advanced computational fluid dynamics for textured surface

analysis. A systematic review is conducted on various surface texturing methods, including laser surface texturing, micro/nano-structuring via additive manufacturing (AM), and mechanical or hybrid surface treatments. This research also analyzes the influence of textural geometric features on fluid dynamics, impact angle distribution, and stress modulation, as well as their interactions with the mechanical properties of the substrate material. Furthermore, it explores the improvement in wear resistance and wettability brought about by complementary coating technologies and biomimetic strategies. Experimental characterization methods and numerical modeling approaches for performance evaluation are introduced. Through practical application examples, the current capabilities and challenges are demonstrated, encompassing issues such as durability, large-scale manufacturing, and process optimization. Finally, future research directions are proposed, advocating for an integrated approach that combines surface texturing design, material modification, and advanced modeling to optimize multifunctional resistance under complex erosive and cavitation conditions.

2. Theoretical frameworks for erosion, cavitation, and textured surfaces

2.1 Overview of erosion and cavitation modeling

Multiphase flow simulations for erosion-cavitation synergy rely on Reynolds-Averaged Navier-Stokes (RANS) turbulence closures (SST $k-\omega$, realizable $k-\epsilon$, and etc), empirical erosion models (micro-cutting, deformation, Oka, DNV, Mansouri; Table 1, Figure 2a), and transport-equation cavitation models (Singhal, Schnerr-Sauer, Zwart-Gerber-Belamri; Table 2, Figure 2b) [39,40]. Density-correction methods (DCM, FBDCM) improve unsteady cavitation capture. For capturing shock waves and void collapses critical to cavitation erosion, compressible inviscid solvers with barotropic homogeneous mixture models enable accurate resolution of pressure wave propagation, with wall load evaluation expressed as Eq. (1) [30]:

$$P_{p,k} = \frac{N_{pThr,k}}{N_{tot}}, N_{pThr,k} = \left\{ N_{tot} \mid p_0 > p_{Thr,k} \right\}$$

$$P_{\alpha,k} = \frac{N_{\alphaThr,k}}{N_{tot}}, N_{\alphaThr,k} = \left\{ N_{tot} \mid -\frac{d\alpha}{dt} > -\left(\frac{d\alpha}{dt}\right)_{Thr,k} \right\} \quad (1)$$

where $P_{p,k}$ represents the pressure erosion probability, p_0 represents the current pressure value, N_{tot} represents the total number of time steps, $p_{Thr,k}$ represents the peak pressure value of the element wall within the specified analysis time interval, $P_{\alpha,k}$ represents the condensation rate erosion probability, and $(-d\alpha/dt)$ represents the negative time gradient of the vapor volume fraction.

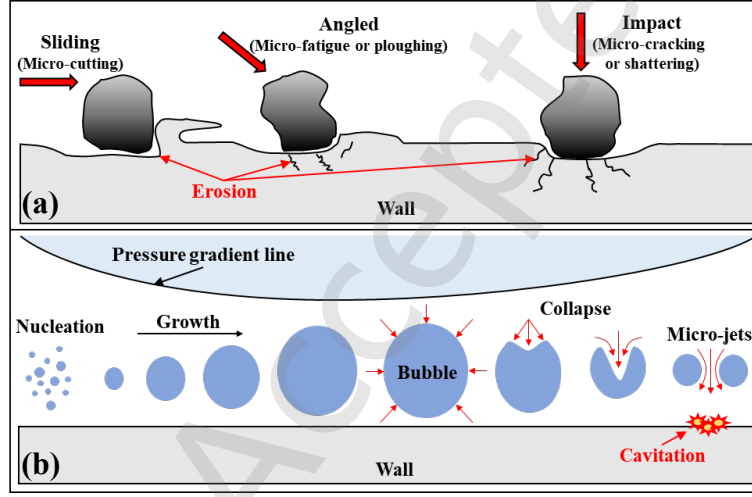


Figure 2. The schematic diagrams of (a) erosive wear mechanism and (b) cavitation erosion mechanism [36].

Table 1. Numerical model for assessing particle erosion.

Model	Equation	Condition	Limitations
Micro-cutting erosion theoretical model [41]	$ER = \frac{m_p v_p^n}{p} f(\theta)$ $f(\theta) = \begin{cases} \sin(2\alpha) - 3\sin^2 \alpha & 0 < \alpha \leq \alpha_0 \\ \frac{\cos^2 \alpha}{3} & \alpha_0 < \alpha < 90^\circ \end{cases}$ ER: erosion rate, m_p: particle mass, v_p: particle impact velocity, p: plastic flow stress, n: particle velocity exponent, α_0: critical incidence angle, α: particle incidence angle.	Based on the micro-cutting theory, it is applicable to erosion prediction for plastic materials under low-angle impact and is widely used in erosion research on metallic materials.	This model attributes erosion solely to micro-cutting, neglecting plastic deformation and fatigue crack propagation, and is thus restricted to brittle materials or high impact angles—yielding severely distorted predictions for ductile materials under deformation-dominated low-angle impacts.
Deformation erosion theoretical model [42,43]	$ER = \frac{m_p v_p^2}{2} \left(\frac{\cos^2 \alpha}{\varphi} + \frac{\sin^2 \alpha}{\varepsilon} \right)$ φ: shear deformation, ε: cutting deformation.	It describes water-borne solid particle erosion, considering impact angle, velocity, and particle shape,	This model considers only plastic deformation and low-cycle fatigue removal, entirely neglecting micro-cutting contributions—thus yielding degraded accuracy in the medium-to-high angle transition regime and for

		for slurry system erosion prediction.	brittle materials, while also omitting time-dependent effects such as work hardening.
E/CRC erosion model [44,45]	$ER = K(BH)^{k_1} F_s v_p^{k_2} f(\alpha)$ K: empirical constant, BH: Brinell hardness, F_s: particle shape factor, k_1: hardness exponent, k_2: velocity exponent.	It takes into account factors such as the hardness of the target material, impact velocity, impact angle, and particle sharpness, and is suitable for erosion prediction of ductile materials.	Based on energy conservation within a two-body wear framework, this model neglects heat, elastic wave dissipation, abrasive rolling, and re-impact effects inherent to three-body wear; moreover, its empirically calibrated coefficients are highly material-specific, severely limiting extrapolation across varying operating conditions.
Oka erosion model [46,47]	$ER = K_p f(\alpha) (HV)^{m_1} v_p^{m_2} d_p^{m_3}$ $f(\alpha) = (\sin \alpha)^{n_1} (1 + HV (1 - \sin \alpha))^{n_2}$ K_p: particle shape and hardness factor, m_1, m_2, and m_3 are identified as the hardness exponent, velocity exponent, and particle diameter exponent, respectively; HV: Vickers hardness, d_p: particle diameter, n_1 and n_2 are determined by material hardness and impact conditions.	Taking into account factors such as impact angle, impact velocity, particle size, and material type, the erosion rate is defined as the product of erosion damage at the impact angle and the impact angle function.	Although incorporating a deformation term, this model rigidly separates cutting and deformation mechanisms, yielding 30%–50% deviations in the intermediate angle regime (20°–45°) where both coexist, while neglecting inter-particle interactions and textured surface effects.
DNV erosion model [48]	$ER = K V_p^n F(\alpha)$ $F(\alpha) = \sum_{i=1}^{i=5} A_i (\alpha)^i$ Values of A_i for $i = 1-5$ are 5.40, -10.11, 10.93, -6.33, and 1.42.	Applicable to erosion scenarios involving high-hardness particles (e.g., sand grains)	Developed for multiphase pipeline flow under smooth-wall assumptions, this model relies on numerous empirically recalibrated constants, entirely neglects texturing, roughness, and coating effects, and shows poor accuracy for non-metallic materials and erosion-cavitation synergy.
Mansouri erosion model [49]	$ER = C (BH)^{-0.59} F_s V_p^n F(\alpha)$ $F(\alpha) = A (\sin(\alpha))^{n_1} (1 + H v_p^{n_2} (1 - \sin(\alpha)))^2$ C is an empirical constant.	Stainless steel 316 (SS316)	As a recent empirical/semi-empirical model, it suffers from narrow validation scope, heavy dataset dependency, unverified extrapolation to textured surfaces and extreme conditions, weak physical interpretability, overfitting risk, and omission of time-dependent material evolution.

Table 2. Numerical model for assessing cavitation.

Model	Equation	Condition	Limitations
Singhal model [50,51]	$\frac{\partial}{\partial t} (f_v \rho) + \nabla \cdot (f_v \rho \mathbf{u}) = \nabla \cdot (\Gamma \nabla f_v) + R_e - R_c$ $R_e = F_{vap} \frac{\max(1.0, \sqrt{k}) (1 - f_v - f_g)}{\sigma} \rho_l \rho_v \sqrt{\frac{2(P_v - P)}{3} \frac{\rho_l}{\rho_v}}$ $R_c = F_{cond} \frac{\max(1.0, \sqrt{k}) f_v}{\sigma} \rho_l \rho_v \sqrt{\frac{2(P - P_v)}{3} \frac{\rho_l}{\rho_v}}$	It takes into account the influences of phase change, bubble dynamics, turbulent pressure fluctuations, and non-condensable gases, making it	Although grounded in the full Rayleigh-Plesset equation, this model requires calibrated evaporation and condensation coefficients (F_{vap} , F_{cond}), produces non-physical results at high void fractions, inadequately captures phase

	f_v : mass fraction of steam; f_g : mass fraction of non-condensable gas; D : diffusion coefficient; R_e : evaporation rate; R_c : condensation rate; F_{vap} : evaporation coefficient; F_{cond} : condensation coefficient.	suitable for the cavitation numerical simulation of heavy oil fluids containing tiny bubbles.	transition under turbulence-cavitation coupling and extreme pressures, and incurs high computational cost.
Schnerr-Sauer model [52]	$\frac{\partial(\rho_v \alpha_v)}{\partial t} + \nabla \cdot (\alpha_v \rho_v \vec{V}) = R_e - R_c$ $R_e = \frac{\rho_v \rho_l}{\rho} \frac{3\alpha_v (1-\alpha_v)}{R_b} \sqrt{\frac{2}{3} \frac{P_v - P}{\rho_l}} (P \leq P_v)$ $R_c = \frac{\rho_v \rho_l}{\rho} \frac{3\alpha_v (1-\alpha_v)}{R_b} \sqrt{\frac{2}{3} \frac{P - P_v}{\rho_l}} (P \geq P_v)$ P: fluid element center pressure, P_v: saturated vapor pressure, ρ_l: liquid density, ρ_v: gas density, α_v: bubble number per volume, R_b: bubble diameter.	Liquid-gas relative motion is ignored, with no-slip wall boundaries. Gravity and heat transfer effects are neglected, assuming an isothermal, incompressible medium throughout the simulation.	Assuming monodisperse bubble radii, this model neglects inherent polydispersity; its empirical parameters (bubble diameter, nucleation site density) lack universality, yielding degraded accuracy at both low and high void fraction extremes.
Zwart-Gerber-Belamri model [53]	$\frac{\partial(\rho_v \alpha_v)}{\partial t} + \frac{\partial(\rho_v \alpha_v u_j)}{\partial x_j} = R_e - R_c$ $R_e = F_{vap} \frac{3\alpha_{nuc} (1-\alpha_v) \rho_v}{R_b} \sqrt{\frac{2}{3} \frac{P_v - P}{\rho_l}} (P \leq P_v)$ $R_c = F_{cond} \frac{3\alpha_v \rho_v}{R_b} \sqrt{\frac{2}{3} \frac{P - P_v}{\rho_l}} (P \geq P_v)$ α_{nuc}: nucleation volume fraction, u: instantaneous fluid velocity.	Higher accuracy, faster convergence, better cavitation erosion forecast.	As a highly empirical model with multiple calibrated constants (F_{vap} , F_{cond} , R_e , R_c , n , F_{nuc}), it yields inaccurate cavitation inception predictions, employs an oversimplified nucleation model neglecting compressibility, performs poorly under extreme pressures and complex flows, and is prone to non-physical cavitation zones.

Particle tracking employs Eulerian-Lagrangian frameworks (RANS + discrete phase model (DPM)/discrete element method (DEM)) with discrete random walk (DRW) turbulence modeling and user-defined function (UDF)-implemented synergistic effects (Figure 3) [54-56]. Computational fluid dynamics (CFD)-DEM coupling with Hertz contact and dynamic mesh methods resolves polydisperse impacts and time-dependent erosion evolution [57-59]. Teran et al. [60] coupled bubble-collapse-induced acceleration (from Rayleigh-Plesset dynamics) with the Grant-Tabakoff model via UDF-augmented DPM, validated by high-speed imaging and volume of fluid (VOF)/degree of freedom (DOF) simulations [61]. Nahon et al. [24] identified micro-jets and collapse pressure waves as two bubble-scale damage mechanisms; Wu et al. [62] showed bubble collapse time increases with decreasing wall elastic modulus (Figure 4). O'Sullivan et al. [63] provided acoustic intensity and particle image velocimetry (PIV) velocity data essential for validation (Figure 5). Cavitation intensity

is assessed via cavitation number ($\sigma = \frac{P_e - P_v}{1/2 \rho V_{th}^2}$, where P_e is downstream pressure, P_v

represents vapor pressure, ρ signifies density, and V_{th} indicates the velocity at the area where cavitation occurs) and discharge coefficient (C_d) [64], with Schnerr-Sauer mass transfer validated at 99.5% accuracy for bubble cycle prediction [65]. Empirical correlations for cavitation length (L_c) and volume (V_c) via RSM are given in Eqs. (2) and (3) [64]:

$$L_c = 190.33 - 42.11\theta + 12.58(W/H) + 14.54(L/H) - 0.52\theta(W/H) - 1.38\theta(L/H) - 1.69(L/H)(W/H) + 2.71\theta^2 - 0.76(W/H)^2 + 1.80(L/H)^2 \quad (2)$$

$$V_c = 5.11 - 1.31\theta + 0.48(W/H) + 84.34(L/H) - 0.02\theta(W/H) - 0.07\theta(L/H) - 0.07(L/H)(W/H) + 0.08\theta^2 - 0.01(W/H)^2 - 0.02(L/H)^2 \quad (3)$$

where θ is the divergence angle, W/H is the throat width/height, and L/H is the throat length/height. These models have been validated against slurry pot, ultrasonic, and jet erosion tests [40,54-56,58,59].

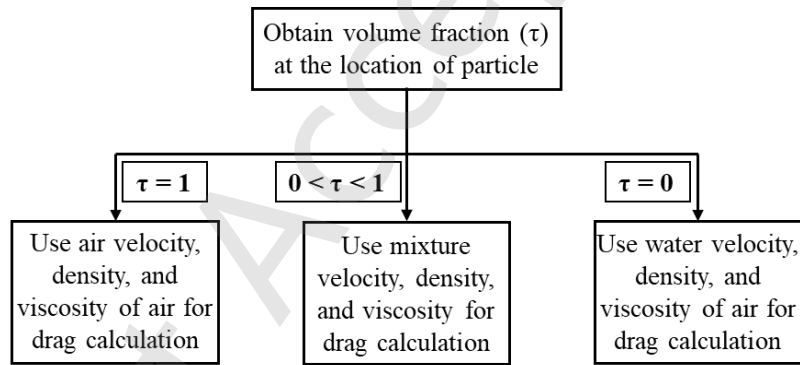


Figure 3. Algorithm employed for the tracking of particles in multiphase flow systems [54].

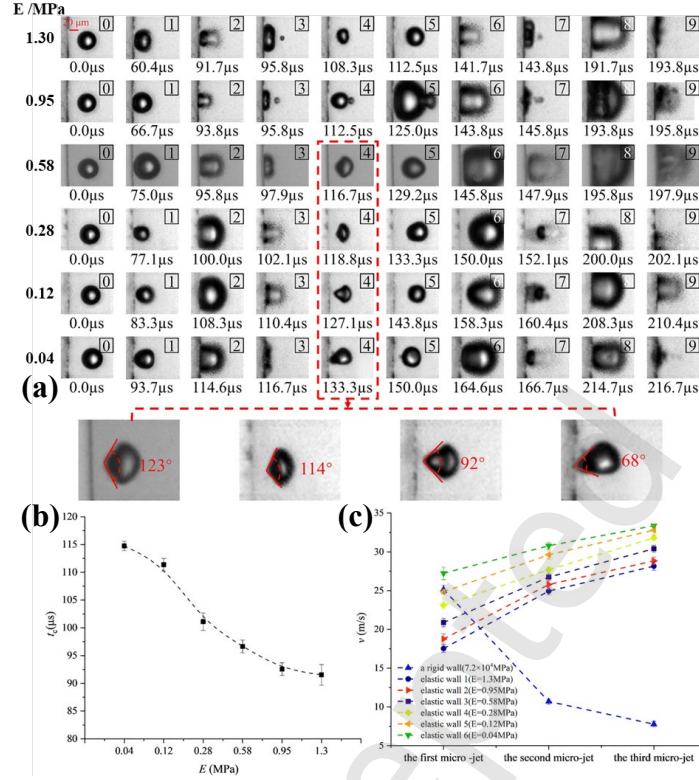


Figure 4. (a) Bubble dynamic behaviors, (b) collapse time, and (c) microjet velocities near elastic walls with varying E values [62].

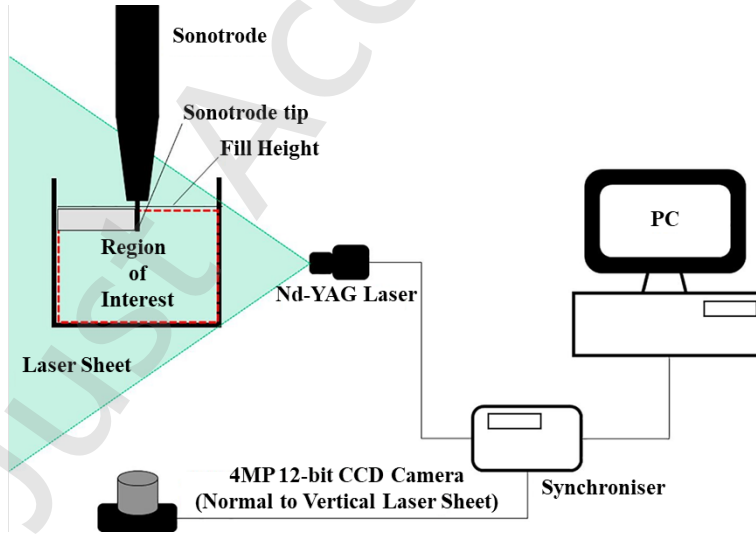


Figure 5. Schematic diagram of the experimental setup [63].

2.2 Theoretical modeling of textured surfaces

Textured surfaces modify the near-wall flow field, alter bubble collapse dynamics, and redistribute particle impact locations, thereby mitigating erosion-cavitation damage. Theoretical modeling of such surfaces requires coupling geometric representation with multiphase flow and erosion physics.

2.2.1 Geometric representation of surface textures

Texture geometries are typically classified as periodic (dimples, grooves, pillars) or stochastic (random roughness). Analytical descriptions employ sinusoidal profiles [66], spherical cap dimples [67], or arbitrary roughness distributions [68]. A hybrid CFD-data-driven framework is developed using Gaussian Process Regression (GPR) to predict slip velocity and velocity offset as explicit functions of texture parameters, with particular emphasis on texture spacing and solid fraction, facilitating physics-based wall function modification [69]. The texture aspect ratio ($A=d/h$, where d is dimple diameter and h is depth) and area density (S_d , fraction of textured area) govern the hydrodynamic response [70].

2.2.2 Flow field modification of textured surfaces

Textured surfaces achieve synergistic suppression of erosion and cavitation through active manipulation of near-wall turbulent structures, the core of which resides in the multi-scale coupled intervention of wall shear stress, wall-normal fluctuations, and gas-liquid interfacial dynamics. At the shear suppression level, configurations such as V-shaped grooves hinder momentum exchange between high- and low-speed fluid regions by inducing secondary vortices, thereby stabilizing low-speed streaks within the groove valleys and attenuating turbulent burst intensity. This directly reduces the wall shear stress fluctuation amplitude and consequently weakens the erosion driving force (Figure 6) [71]. At the fluctuation attenuation level, surface texturing induces a wall-normal displacement of quasi-streamwise vortices (quantified by ℓ_{uv}^+), which exhibits a linear dependence on the permeability factor. This displacement effectively attenuates both the amplitude and spectral content of wall-normal velocity fluctuations, thereby reducing the directionality and impact intensity of microjets generated by cavitation bubble collapse [72]. At the interface stabilization level, superhydrophobic textures sustain a local high-pressure environment via an entrapped air film, thereby elevating the cavitation inception threshold. The stability of this air film is governed by the critical pressure p_{cr} ; however, when the texture scale exceeds $L^+ \gtrsim 25$, nonlinear

coupling between upstream-propagating capillary waves and texture-coherent flows becomes the dominant mechanism triggering air film destabilization [73,74]. These three effects are unified through a slip-permeability coupled boundary condition: the transpiration–resistance model (TRM) abstracts the macroscopic texturing effects into a coupling of the streamwise protrusion height ℓ_u^+ and the spanwise protrusion height ℓ_w^+ , where the velocity profile offset $\Delta U^+ = \ell_u^+ - \ell_w^+$ quantitatively characterizes the synergistic modulation of mean-flow drag and turbulent fluctuation response by the texture [72]. Dimple arrays, in contrast, follow an alternative pathway by generating separation bubbles and triggering shear layer instabilities to control flow reattachment, yet their effectiveness is strictly constrained by the matching of Reynolds number and geometric parameters [75]. The principal gap in current theory lies in the fragmented treatment of these mechanisms, with no closed-loop coupled model integrating shear modification, fluctuation attenuation, and interface dynamics. This deficiency is particularly acute when $L^+ \gtrsim 25$, where texturing transitions from a passive boundary condition to an active source term in the Navier-Stokes equations [76,77], necessitating a cross-scale design paradigm unified by the metric of near-wall turbulence modification effectiveness.

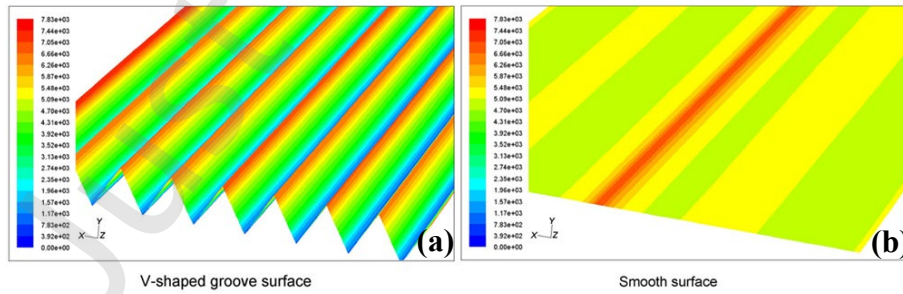


Figure 6. Shear stress on the (a) textured and (b) smooth surfaces [71].

3. Surface texturing techniques for enhancing particle erosion and cavitation erosion resistance

3.1 Laser surface texturing and induced micro/nano-structures

3.1.1 Laser types and fundamental mechanisms in surface texturing

Laser surface texturing (LST) is a versatile technique for fabricating micro/nano-scale surface structures (Figure 7), with ultrashort pulsed (USP) lasers such as

picosecond and femtosecond lasers being widely utilized due to their advantages of minimal heat load, reduced heat-affected zones, and high precision [78]. These lasers, along with nanosecond lasers, enable the creation of diverse surface morphologies tailored to specific applications. Picosecond laser texturing, for instance, has been employed to generate cone-shaped and broccoli-like pillars on glass substrates, periodic line-like structures on metals via direct laser interference patterning (DLIP) [79], and controllable micro-pits and grooves on metal substrates, where depth and width positively correlate with laser power and scanning times [80,81]. Femtosecond lasers, on the other hand, are capable of producing laser-induced periodic surface structures (LIPSS), including low-spatial-frequency LIPSS (LSFL) with periods close to the laser wavelength and high-spatial-frequency LIPSS (HSFL) with smaller periods, as well as cone-like protrusions (CLP) [82]. Nanosecond lasers, though more cost-effective, induce stronger thermal effects, resulting in structures like chaotic micrometer-scale roughness with splashed material islands.

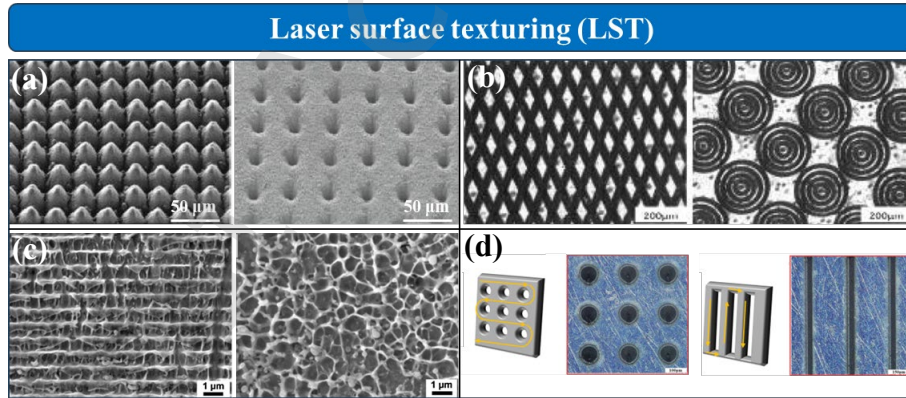


Figure 7. Diverse surface microstructures fabricated via laser processing [78-80]: (a) micro-bumps and micro-pits, (b) rhombus and circular ring, (c) line-like structure, and (d) micro-pits and micro-grooves.

3.1.2 Surface morphology engineering via laser parameter optimization

On surfaces of different materials, the surface morphologies induced by laser texturing exhibit significant differences due to variations in laser types and parameters. Circular textures with a diameter of 50 μm and pitch of 200 μm have been fabricated on high-velocity oxy-fuel (HVOF)-sprayed vanadium carbide (VC) coatings using a

fiber laser [83], while micro-grooves with an average diameter of 50 μm and no microcracks or pores were developed on carbide surfaces [84]. On martensitic stainless steel (SS410), circular and diamond-shaped micro-textures have been created, and hierarchical micro/nano-structures, such as micro-grooves and micro-pit arrays with spherical nanoparticles (~ 100 nm diameter), were formed on AISI304 stainless steel via picosecond laser texturing [85]. For ceramic coatings, picosecond laser texturing produced precise micro-grooves (groove distance: ~ 150 μm , depth: ~ 50 μm , width: ~ 50 μm) on $\text{Al}_2\text{O}_3/\text{TiC}$ coatings with minimal surface damage [86]. Picosecond laser texturing on Ti6Al4V alloy produced bumpy, pillow-like, and hole structures with size scales from hundreds of nanometers to micrometers, while nanosecond laser texturing resulted in chaotic roughness with splashed material [87].

3.1.3 Laser-induced microstructure refinement enhances surface hardness

Regarding surface hardness, laser texturing can either maintain or enhance the hardness of the substrate depending on the material and processing parameters. For example, laser textured VC coatings on SS316 steel exhibited similar microhardness to the as-sprayed HVOF coating, while circular-inward textured SS410 stainless steel showed the highest hardness ($\sim \text{HV}_{0.3} \approx 206$) due to microstructure alteration from rapid cooling after laser melting and evaporation [88]. Laser textured Ti6Al4V alloy surfaces also demonstrated increased microhardness, with smaller texture step sizes leading to higher hardness attributed to grain refinement and increased grain boundaries [87].

3.1.4 Wettability transition: From hydrophilic to superhydrophobic surfaces

Wettability is significantly influenced by laser-induced surface structures, often transitioning from hydrophilic to hydrophobic or superhydrophobic with appropriate post-treatments. Picosecond laser-textured glass substrates with fluoro-silane coating exhibited superhydrophobic behavior with a water contact angle (WCA) approaching 180° [89]. On HVOF-sprayed VC coatings, laser texturing increased the static contact angle (SCA) from 116° (untextured) to 139° (Figure 8) [83], while the development of pillar-like structures on SS316 steel with HVOF coatings enhanced the static contact

angle. Heat treatment of laser-textured Ti6Al4V surfaces transformed them from superhydrophilic (0°) to superhydrophobic with a WCA of 155.0° [90]. Laser texturing parameters, such as spot overlap, also influence surface properties; for example, 0% overlap laser treatment on AA6082 aluminum alloy resulted in higher hydrophobicity compared to 30% overlap samples [91].

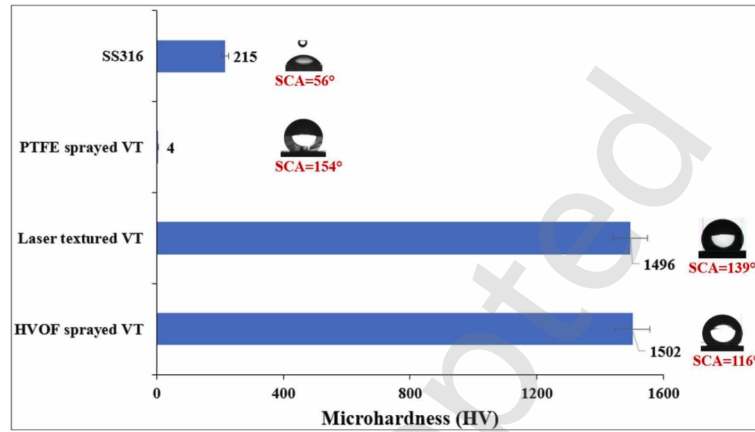


Figure 8. Average Microhardness and SCA of different samples [83].

3.1.5 Tribological performance improvement: Erosion resistance and friction reduction

Tribological properties, including erosive wear resistance and friction, are markedly improved by laser texturing. The circular textures on VC coatings altered slurry flow characteristics, reducing contact area with slurry particles and mitigating erosive effects. Similarly, micro-grooves on $\text{Al}_2\text{O}_3/\text{TiC}$ coatings limited crack propagation during erosion, reducing cumulative mass loss by up to 45% (Figure 9) [86]. Laser-textured SS410 stainless steel with circular-inward micro-textures showed enhanced slurry erosion resistance due to increased hardness and swirl motion of slurry over micro-textures. Laser textured Ti6Al4V surfaces with a step size of $150\text{ }\mu\text{m}$ achieved a 33.9% improvement in liquid-solid two-phase flow erosion resistance after heat treatment [92]. Additionally, femtosecond laser-fabricated LIPSS on various materials have been observed to increase friction coefficients by factors up to 3.5 due to increased roughness and tribo-chemical reactions [93], while squamous textures on silicon carbide (SiC) reduced the coefficient of friction (COF) by up to 18.9% under mixed lubrication [94]. The combination of laser texturing and PTFE coating on VC surfaces further enhanced wear resistance by forming a thin non-stick layer, reducing

particle adhesion and friction [95]. Texture-induced cavitation in journal bearings was found to reduce lubricant effective viscosity and shear stress, lowering friction coefficients [96]. Other surface texturing methods, such as abrasive jet machining, have also been explored, but laser surface texturing offers unique advantages in precisely controlling micro/nano-structures relevant to particle erosion and cavitation erosion resistance [97,98].

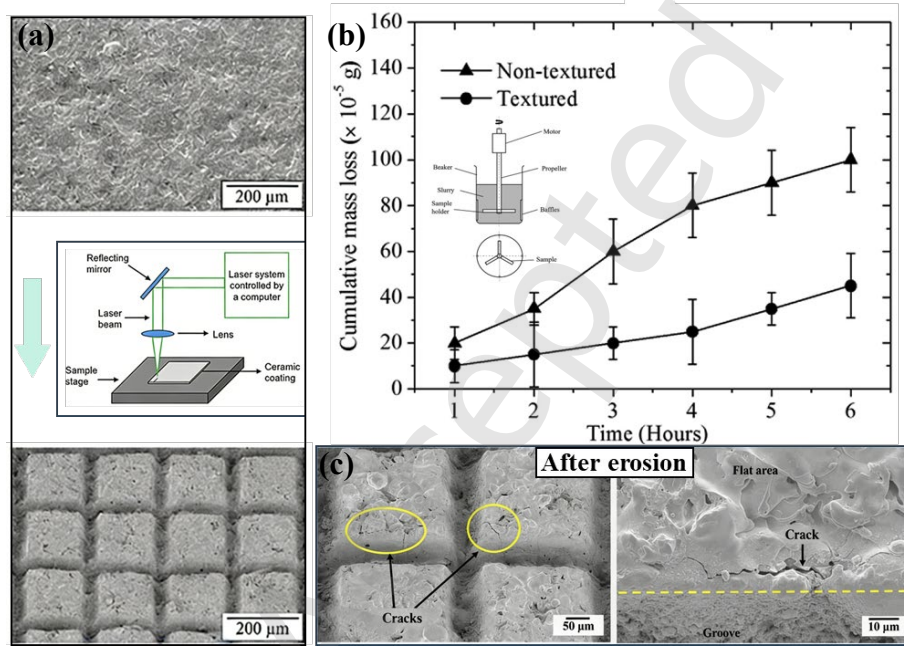


Figure 9. (a) Laser-processed micro-groove texture; (b) mass loss curve and (c) scanning electron microscopy (SEM) image after erosion testing [86].

3.2 Additive manufacturing surface textures

3.2.1 Layer-by-layer fabrication: Design freedom and process parameter optimization

AM, such as 3D printing, plays a pivotal role in fabricating precise surface textures by enabling the direct creation of complex patterns during the production stage without the need for secondary surface preparation processes. This technology offers enhanced design freedom and manufacturing flexibility, allowing the construction of intricate micro- and nano-structures layer-by-layer from digital models, with adjustable process parameters (e.g., extrusion speed and temperature) to improve surface quality and dimensional accuracy [99]. It is applicable to a wide range of materials, including metals, ceramics, and polymers.

3.2.2 Erosion resistance enhancement: Experimental validation

Experimental studies have demonstrated the efficacy of 3D printed surface textures in reducing erosion. For instance, wear tests on 3D printed high-impact polystyrene surfaces with mesoscale textures (uniformly distributed pits and bumps) showed up to 77% wear reduction compared to the worst-performing sample, with DEM simulations validating the influence of geometric characteristics on abrasive particle movement and contact stress distribution [100]. In solid particle erosion tests, 3D printed macro-textured ABS polymer surfaces designed according to erosion direction reduced particle erosion by approximately 71% when the erosion direction was perpendicular to the texture, attributed to mechanisms such as kinetic energy loss of particles post-impact, obstruction of incoming particles by rebounding particles, and an "air cushion" effect altering gas-particle flow (Figure 10) [37]. For cavitation erosion, rectangular pocket micro-textured 17-4PH stainless steel fabricated via laser-powder bed fusion (L-PBF) exhibited 7-8 times greater resistance to ultrasonic cavitation erosion (CE) and cavitation erosion-corrosion (CEC) compared to flat AM samples, driven by shockwave dampening (Figure 11) from liquid micro-reservoirs in the pockets and residual compressive stresses (-135.8 MPa) induced by the texturing process [38].

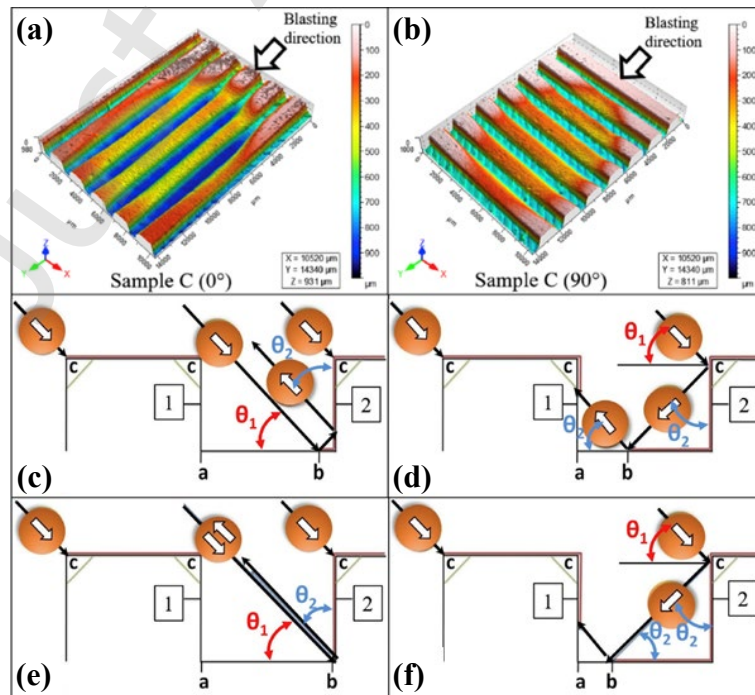


Figure 10. Surface morphologies of textured samples after erosion at (a) 0° and (b) 90° orientations; schematic diagrams of abrasive particle trajectories in groove-textured surfaces: (c, d) with lower groove height and (e, f) with higher groove height [37].

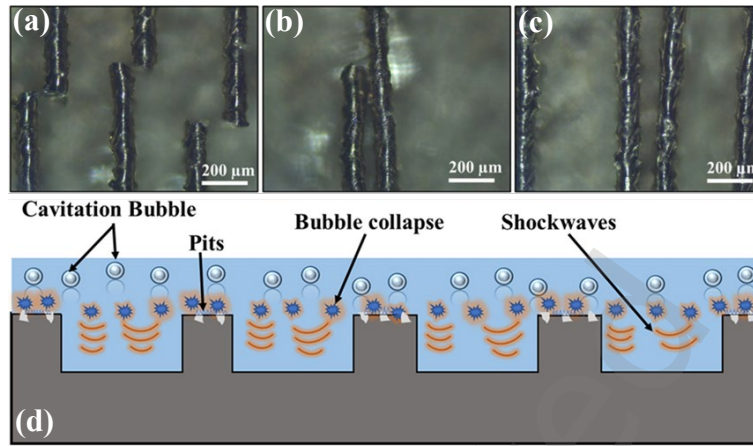


Figure 11. (a-c) Fracture morphologies in distinct regions of textured samples after 5 h CE testing and (d) schematic illustration of cavitation bubbles near the sample surface [38].

3.2.3 Comparative analysis

When compared to conventional texturing methods, 3D printed surface textures present both advantages and limitations. They offer a practical alternative to thin film coatings, which suffer from uneven coverage on 3D shapes and film detachment, by providing improved durability and wear resistance. However, 3D printing faces challenges such as high equipment and material costs, material limitations (e.g., feasible metals restricted to alloys like AlSi10Mg and TiAl6V4), and lower surface quality/accuracy relative to traditional machining methods like milling. Milling remains superior in precision, cost, and efficiency for surface texturing, particularly for large-area applications [101]. Conventional methods like laser processing can also create precise textures, such as hundreds-micron scale rectangular array grooves on 17-4PH stainless steel that enhance cavitation erosion resistance [31], and laser-fabricated textures on metal lap surfaces that improve joint strength via mechanical anchoring [102]. Additionally, surface roughness, a critical parameter in both AM and conventional processes, significantly impacts erosion behavior; for example, increasing surface roughness from 1 μm to 60 μm on aluminum alloy compressor blades led to diffused wear areas and increased maximum wear rates [103]. In addition to surface

roughness, the inherent residual porosity in AM processes adversely affects cavitation performance. Studies have demonstrated that residual pores may serve as nucleation sites for cavitation bubbles, where bubbles form during liquid flow, rapidly expand, and collapse, generating high-impact forces that induce crack initiation and propagation, thereby degrading cavitation erosion resistance [104,105]. Consequently, when employing AM to fabricate surface textures, appropriate measures to minimize residual porosity are essential to enhance cavitation erosion resistance. The design of texture parameters (e.g., groove width ratio and film thickness ratio) is critical for hydrodynamic performance [106], and numerical models for texture optimization [107,108] provide theoretical guidance that can be implemented using AM's precise fabrication capabilities.

3.3 Surface texturing via single or hybrid mechanical treatments

Single mechanical and hybrid surface texturing treatments encompass a range of techniques that induce favorable surface textures and residual stresses to enhance particle erosion and cavitation erosion resistance. Shaping and stamping processes have been employed to prepare textured surfaces on carbon steel, creating trapezoidal and rasp shapes, which, when combined with nitriding heat treatment (a hybrid approach), form an iron nitride layer via nitrogen diffusion to increase surface hardness. This hybrid treatment significantly reduces erosion by 40%-50% for trapezoidal textures and 15%-17% for rasp shapes, with erosion resistance influenced by the synergistic effect of hardness and texture patterns [109].

3.3.1 Single mechanical technique

For example, shot peening (SP) is a mechanical technique, as demonstrated on nickel-aluminum bronze (NAB), where it induces microstructural refinement, strain hardening, and compressive residual stresses (increasing from -85 MPa to up to -444 MPa at higher intensities). SP-treated NAB shows reduced erosion corrosion (EC) mass loss rates by 25% and 30% at intensities of 0.1 and 0.2 mmA, respectively, though excessive treatment (dual SP) can lead to brittle cleavage-like fractures and worsened

EC performance [110]. Oil jet peening, applied to aluminum alloys AA6063-T6 and AA6061-T4, induces surface plastic deformation via repeated oil droplet impacts, forming small truncated-sphere indents with circumferential rims. This process achieves high coverage (up to 100%) with smaller indent sizes and less surface roughening compared to conventional shot peening, particularly in higher yield strength materials like AA6063-T6, due to the cushioning effect of oil [111]. Slide diamond burnishing (SDB), similar to ball burnishing but using a spherically finished diamond tip, effectively reduces surface irregularities, increases the radii of irregularity peaks, and enhances bearing surfaces. For hardened alloy steels, SDB reduces steady wear by 20-40% compared to polished specimens, making it suitable for low-stiffness elements like valve stems [112].

3.3.2 Hybrid mechanical treatments

Hybrid mechanical treatments combine mechanical deformation with other effects to enhance texture and residual stresses. The ultrasonic surface rolling (USR) process, which combines high-frequency ultrasonic vibration with static rolling load, has been applied to 42CrMo steel, inducing grain refinement (average grain size reduced from 6.06 μm to 2.46 μm after 12 passes), increased microhardness (up to 487.3 HV), and deep compressive residual stresses (up to -552.19 MPa). These changes inhibit crack initiation and propagation, significantly improving cavitation erosion resistance, though excessive deformation can induce rolling fatigue defects (Figure 12) [113]. USR further involves shock wave pressure from bubble collapse during cavitation, with shock wave pressures reaching up to 416.07 MPa at a 5 μm amplitude, playing a dominant role in surface strengthening through plastic deformation and residual stress formation [114]. Ultrasonic vibration techniques also contribute to texture modification and erosion resistance. For instance, ultrasonic vibration devices have been used to study cavitation erosion in Inconel alloys, where Inconel 625 exhibits better resistance due to higher microhardness and elastic modulus from intermetallic compounds. Increased surface roughness from such treatments enhances hydrophobicity, accelerating bubble

dynamics and cavitation damage [115]. Additionally, ultrasonic cavitation deburring leverages micro-jet impacts, with a mathematical model relating impact pressure to process parameters (working gap, ultrasonic amplitude), achieving up to 92.1% burr removal within 40 seconds when impact pressure exceeds the material's yield strength [116].

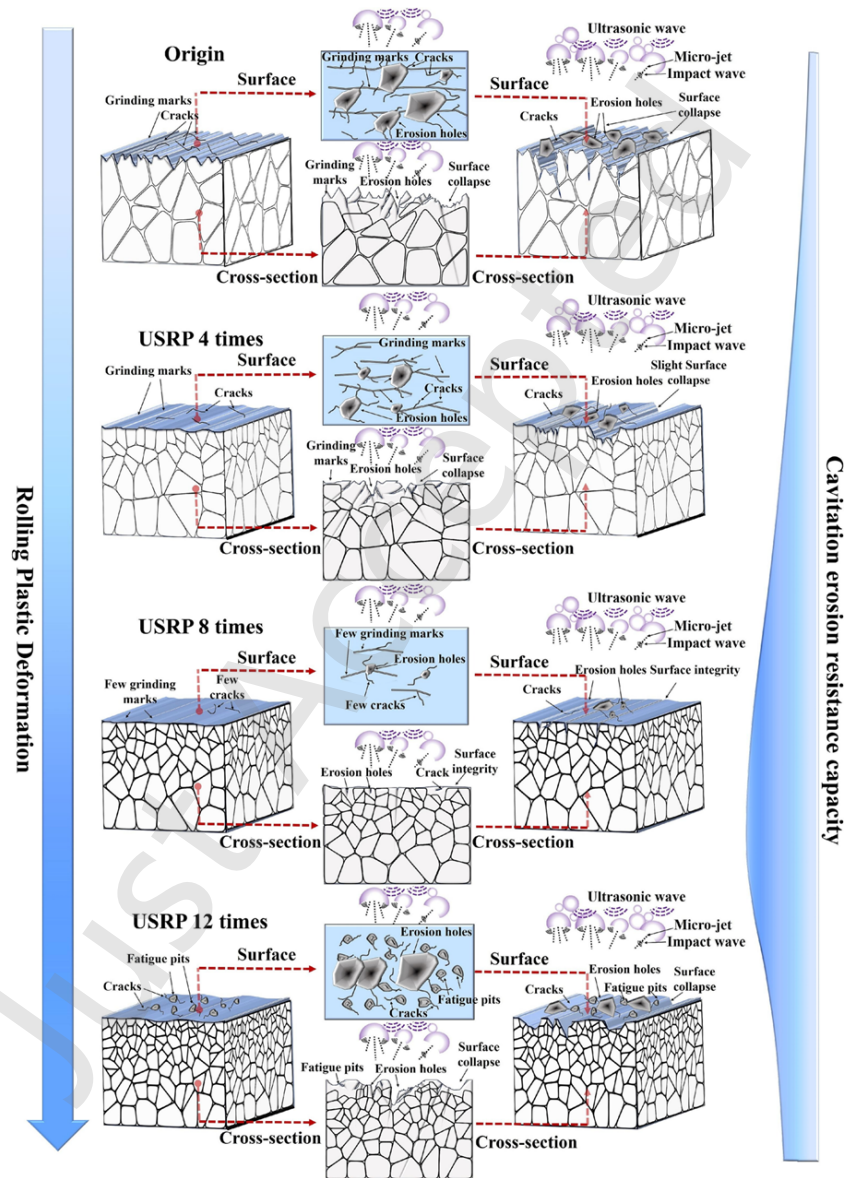


Figure 12. Schematic diagram of cavitation erosion resistance mechanism [113].

Numerical modeling supports the design of hybrid textures, as seen in the study of hydrodynamic journal bearings with rectangular dimples (macro-texture) and micro-dimples (micro-texture). This combined texture model improves load capacity and reduces friction coefficient by spatially controlling texture distribution, highlighting the

significance of geometry and micro-texture detail for enhanced particle erosion and cavitation erosion resistance [117].

4. Coating technologies and material modifications complementing surface texture

4.1 HVOF sprayed coatings and composite layers

HVOF spraying is a process in which partially or fully melted coating granules are propelled toward the base material using high-velocity gas, aiming to prepare a coating of substantial thickness. This coating has been shown to possess high hardness and bonding strength. A range of HVOF coatings, including VC, titanium carbide (TiC), CuNi-Cr, and tungsten carbide (WC), have been explored for enhancing surface properties. For example, HVOF sprayed VC and CuNi-Cr coatings on SS316 steel, with or without laser texturing (Figure 13), have been demonstrated to enhance surface hardness and improve slurry erosion resistance [84].

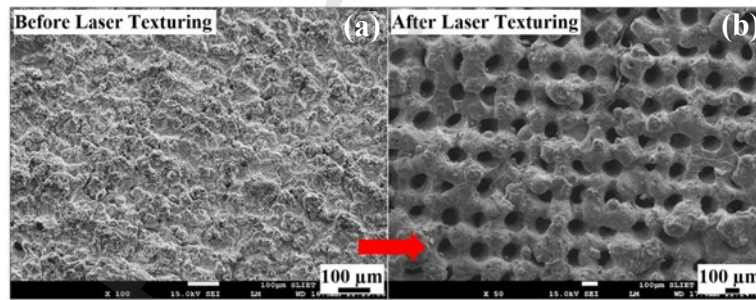


Figure 13. SEM images: (a) VC coating without texture, (b) VC coating with texture [84].

In the development of composite coatings, HVOF spraying has been utilized to deposit VC-TiC and CuNi-Cr based coatings on SS316 steel substrates. Prepared samples included VT (100% VC+TiC), VT50C (50% VC+TiC + 50% CuNi-Cr), and C (100% CuNi-Cr). Results indicated that VC-TiC based coatings significantly enhanced the slurry erosion resistance of SS316 steel used in hydromachinery, while CuNi-Cr coatings also showed good bonding and contributed to improved slurry erosion resistance [118]. Furthermore, combining HVOF coatings with laser texturing can produce superhydrophobic surfaces, further increasing resistance to slurry erosion by increasing the static contact angle and altering failure.

It is worth noting that HVOF coatings inherently develop a micro-scale roughness

profile during the deposition process, which exerts a significant influence on subsequent hydrophobic treatments. A moderate degree of micro-roughness provides a favorable foundation for the construction of superhydrophobic surfaces; by decorating the rough surface with low-surface-energy substances, stable superhydrophobic structures can be formed, effectively reducing the contact area between the liquid and the material surface and thereby enhancing cavitation erosion resistance. However, excessive or non-uniformly distributed roughness may compromise the effectiveness of hydrophobic treatment, adversely affecting the stability of the superhydrophobic surface and its cavitation erosion resistance. Consequently, precise control of the micro-roughness of HVOF coatings is essential when pursuing superhydrophobic surface modification.

4.2 Superhydrophobic and superhydrophilic functional surfaces

4.2.1 Impact of wettability and adhesion reduction

The integration of surface texturing with wettability modification has emerged as a promising approach to reduce adhesion and mitigate cavitation damage by tailoring both surface roughness and surface energy. Low-pressure plasma treatments, for instance, enable simultaneous surface chemistry modification and texturing, where preferential chemical erosion of amorphous zones leads to selective etching, creating surface morphology that improves adhesion. For PEEK surfaces, O₂ plasma generates texture via chemical erosion, while Ar plasma primarily causes material etching with thermal effects altering crystallinity, and laser texturing produces well-defined geometric patterns (e.g., hexagonal arrays of holes) with secondary random texture on inner walls favorable for mechanical anchoring of metallic films; the laser-induced thermal altered zone (TAZ) contains ripples associated with photothermal effects, further influencing surface morphology and adhesion [119]. Wettability of such plasma- or laser-textured PEEK surfaces, characterized by CA measurements using water and diiodomethane (using surface free energy components computed through the Owens-Wendt method), directly relates to surface chemical and morphological changes

introduced by the treatments, and integrating texturing with chemical functionalization results in surfaces with tailored roughness and surface energy that together influence interfacial adhesion, reducing adhesion loss linked to cavitation and wear mechanisms.

4.2.2 Achieving superhydrophobicity by laser texturing

Laser texturing, in particular, creates hierarchical micro/nano-patterned surfaces that initially exhibit superhydrophilicity but transform to superhydrophobicity after post-treatments such as airborne organic contamination, low-temperature annealing, or silanization (e.g., fluoroalkyl silanes or silicone sol modifications to reduce surface energy). These superhydrophobic laser-textured surfaces exhibit reduced adhesion forces (van der Waals, solid-liquid adhesion, electrostatic) due to the reduced liquid-solid contact area provided by hierarchical textures combined with chemical modifications; mechanistically, air pockets trapped in the laser-created micro/nano structures induce a Cassie-Baxter wetting state, minimizing liquid adhesion and thus cavitation damage. Concrete examples include aluminum alloy surfaces with picosecond laser-textured hierarchical patterns showing water contact angles around 162° (exhibiting excellent anti-icing ability) and stainless steel surfaces treated with picosecond/femtosecond laser texturing plus fluoroalkyl silane modification achieving contact angles of 160 - 165° with durable superhydrophobicity and antibacterial function [78]. Such surfaces demonstrate superior corrosion resistance and chemical stability under cavitation and abrasive wear, making them potential for use in heavily loaded hydraulic systems, with hierarchical textures and wettability modifications also contributing to self-healing properties by maintaining hydrophobicity despite mechanical abrasion.

4.3 Biomimetic and multilayer morphology-material coupling

Biomimetic design principles for enhancing particle erosion and cavitation erosion resistance draw inspiration from natural surfaces that have evolved to withstand harsh environmental conditions, with implementation focusing on coupling surface morphology and material properties to achieve synergistic performance improvements.

Zhang et al. [18] designed a novel morphology-material coupled biomimetic anti-erosion surface by leveraging the anti-erosion characteristics of *Parabuthus transvaalicus* and Tamarisk. This design integrates biomimetic surface morphology, consisting of grooves and bumps with geometrical parameters scaled from biological features for practical fabrication, and a multilayer material system mimicking natural structures observed in *Parabuthus transvaalicus*, which includes a hard surface layer and a soft interior layer. A large-area preparation method (Figure 14) was developed to realize this coupled system, involving wire electrical discharge machining for groove creation, electroplating of spherical particles to form bumps, and sequential deposition of soft (copper) and hard (nickel) layers. Sandblasting experiments demonstrated that this biomimetic surface exhibited enhanced erosion resistance at various impact angles, attributed to the synergistic effects of the surface morphology and multilayer material structure, with detailed optimization of the electroplating process ensuring high precision and stability of the spherical particles' bonding and positioning.

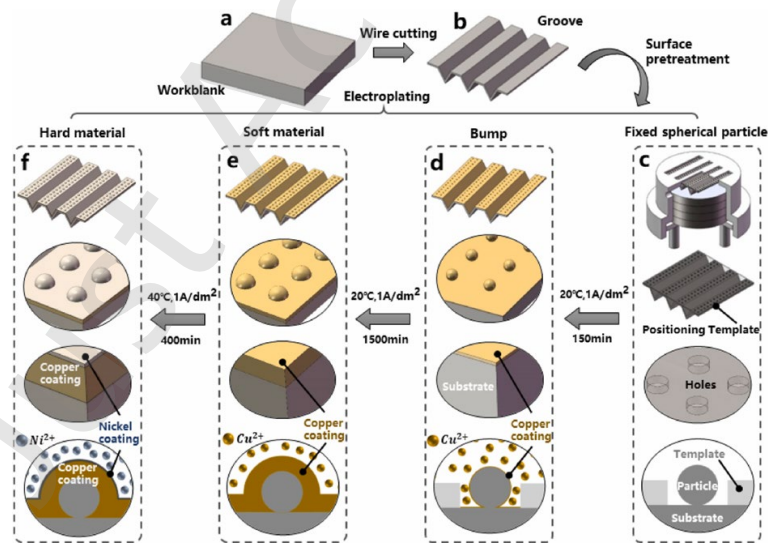


Figure 14. Preparation process of morphology-material coupled bionic anti-erosion functional surfaces [18].

In another approach, Raturi et al. [120] reported an innovative strategy that mimics natural erosion-resistant surfaces by coupling morphology and material modifications (Figure 15), combining severe surface deformation via stationary friction processing (SFP) with subsequent micro-texturing through a micro-imprinting technique to

achieve exceptional cavitation erosion-corrosion resistance on stainless steel surfaces. The processed and micro-textured (SFP+T) surfaces showed erosion resistance 6-7 times greater than as-cast samples under ultrasonic cavitation conditions. This remarkable improvement was attributed to the refined grain microstructure resulting from severe plastic deformation and the altered fluid flow distribution induced by surface texturing, as validated by numerical flow simulations using ANSYS-Fluent. This combinatorial strategy avoids the interfacial defects or delamination issues of coating-based methods and presents a cost-effective, facile pathway distinct from high-cost laser texturing, effectively integrating biomimetic surface texturing principles with severe plastic deformation techniques for enhanced protective behavior under harsh hydrodynamic cavitation conditions.

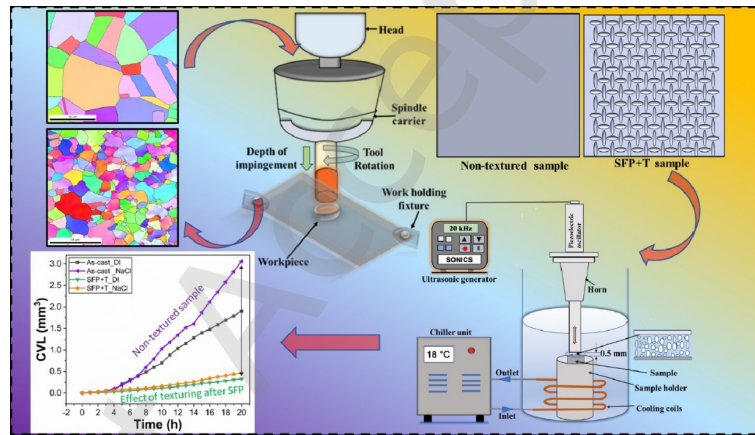


Figure 15. Ultrasonic cavitation erosion behavior of textured stainless steel surfaces [120].

5. Influence of surface texture on particle erosion and cavitation erosion resistance

5.1 Effects of texture geometry, scale, and arrangement

The geometry, scale, and arrangement of surface textures play crucial roles in mitigating erosion and cavitation by modifying impingement dynamics, fluid flow behavior, and stress modulation.

5.1.1 Influence of texture geometry on particle erosion and cavitation erosion resistance

Regarding texture shape, V-shaped grooves with an equilateral triangular cross-section (side length ($a = 4$ mm), spacing ($b = 2$ mm)) have been shown to reduce erosion rates by up to 40% at a global impingement angle of 30° , primarily through diversifying

local impingement angles ($(\theta_1 = \alpha)$, $(\theta_2 = 120^\circ - \alpha)$, $(\theta_3 = \alpha - 60^\circ)$), while secondary effects like multiple particle impacts and air swirls were found negligible (Figure 16a-d) [17]; during erosion wear experiments conducted with erosive particles ranging in diameter from 75 to 100 μm , the rhombus groove textures (widths: 50 μm , 75 μm , 100 μm , and 125 μm (Figure 16e), uniform depth: 50 μm) effectively altered the motion trajectories of the erosive particles, deflected their impact paths, and optimized the turbulent kinetic energy distribution on the metal surface, thereby significantly reducing the degree of erosion wear (Figure 16f) [81]. For slurry jet erosion, circular-inward laser surface texturing (LST) on stainless steel SS410 (depth ~ 40 μm) exhibited higher hardness ($\text{HV}_{0.3} \approx 206$) and superior erosion resistance compared to diamond-inward textures, attributed to swirling slurry motion (air cushion effect) that reduces abrasive impact [88]. Among rectangular, V-shaped, and elliptical microgrooves, rectangular grooves are more suitable for stressed structures due to moderate stress concentration and effective energy dissipation, whereas V-shaped grooves suffer severe stress concentration at the bottom (often exceeding yield stress) and elliptical grooves show higher top surface stress [121]. In 3D-printed ABS and PLA, cone textures outperformed prism (rectangular) textures in erosion resistance, with impact velocity and particle size ranking as more influential parameters than texture geometry [122]. For cavitation erosion, rectangular microgrooves (400 μm period) demonstrated better resistance than triangular ones (75 μm period) by regulating pressure fluctuations and bubble dynamics [123], while rectangular pocket micro-textures (200 $\mu\text{m} \times 200$ μm , depth ~ 185 μm) on 17-4PH stainless steel achieved 7-8 times greater cavitation erosion (CE) and cavitation erosion-corrosion (CEC) resistance than linear channels, as the pockets act as micro-reservoirs to dampen shockwaves [38]. However, laser-textured micro-dimples (100 μm diameter, 20 μm depth, 250 μm spacing) on AlSi10Mg showed higher cavitation erosion rates than turned or polished surfaces, indicating texture geometry may not always enhance resistance [124].

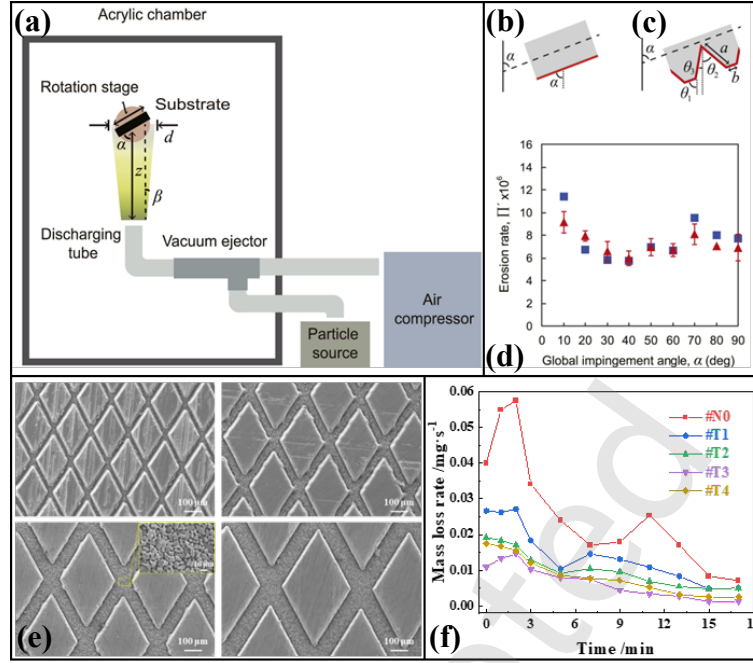


Figure 16. (a) Schematic diagram of the particle erosion experimental setup, local impact angles on (b) a smooth surface and (c) a grooved surface; (d) Surface erosion rate [17]; (e) SEM images of rhombus textures and (f) the mass loss rate after erosion tests [81].

5.1.2 Impact of scale parameters on performance

Scale parameters, including groove width, depth, spacing, and period, significantly affect performance. Millimeter-scale textures exhibit ~10 times higher load-carrying capacity than micrometer-scale ones, with a high depth-to-diameter ratio ($H = 1$) beneficial at low speeds ($V < 10$ m/s) [125]. For rectangular array grooves on 17-4PH stainless steel subjected to cavitation erosion tests using an ultrasonic cavitation system (Figure 17a-c), cavitation erosion resistance increases with the groove width-to-spacing ratio (L/W), with the highest ratio (1.75) showing the longest incubation period (25.05 h) and minimal cumulative mass loss (10.92 mg after 50 h) [31]. Optimal cavitation erosion resistance was achieved with a groove period of 800 μm and ($L/W = 1$), where cumulative mass loss correlates with fluid flow on the groove surface (Figure 17d) [65]. In biomimetic surfaces, grooves (width 4 mm, depth 3.46 mm) and bumps (diameter 800 μm) with spacing equal to their characteristic sizes (width-to-bump diameter ratio 5:1) enhance erosion resistance when combined with multilayer materials [18]. Micro-imprinted textures using a wire mesh template (wire diameter ~90 μm , pitch 150 μm),

combined with severe surface deformation, achieved 6-7 times higher cavitation erosion resistance by improving fluid flow distribution and surface hardness [120].

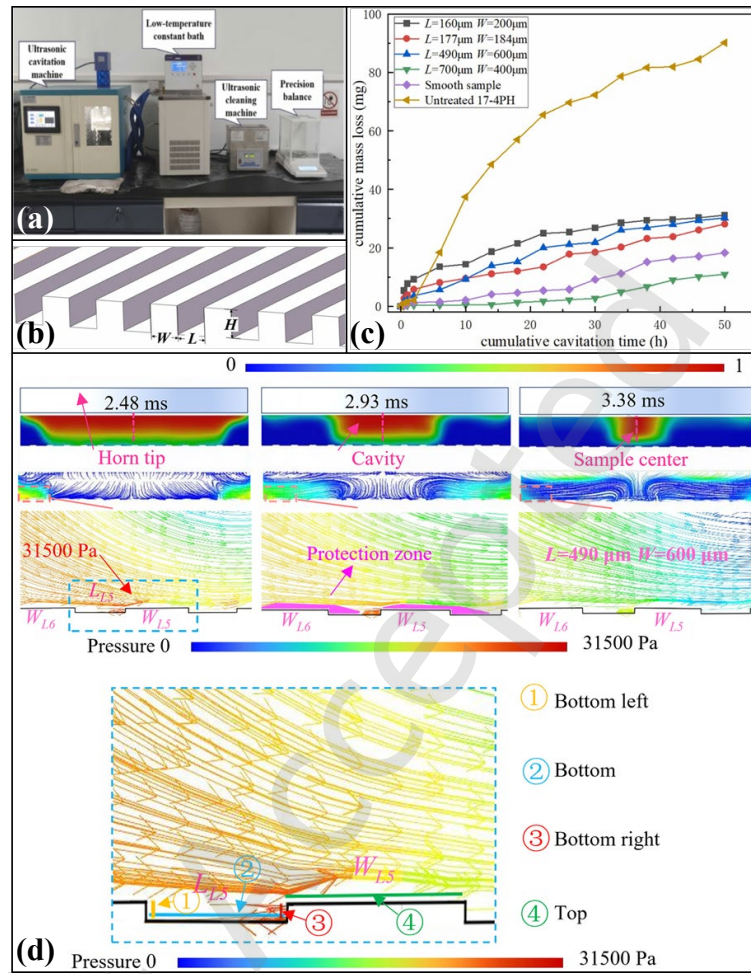


Figure 17. (a) Ultrasonic cavitation system, (b) groove geometry, and (c) mass loss curves [31]; simulation results of the cavitation collapse process within the time range of 2.48 ms to 3.38 ms [65].

5.1.3 Role of pattern distribution and arrangement in erosion mitigation

Pattern distribution and arrangement also influence erosion mitigation. Multi-holed orifice plates with four alternately arranged holes eliminated cavitation under the same operating conditions, outperforming single-holed designs [126]. For micro-texture arrays, parallelogram patterns achieved maximum bearing capacity at 6 m/s, with single symmetric orientation (optimal tilt angle $\sim 26.6^\circ$) providing the best lubrication and up to 29.4% friction reduction [127]. At valve ports, grooves reduced cavitation intensity under inlet pressure fluctuations, with two-step throttles (chamfered seat with groove) showing better anti-cavitation ability than single-step designs [128].

Additionally, groove-shaped flow velocity distributions induced by impact angles influence local erosion patterns: oblique angles lead to elliptical erosion profiles, while normal impact causes circular ring erosion due to backpressure-induced stagnation points (Figure 18) [56].

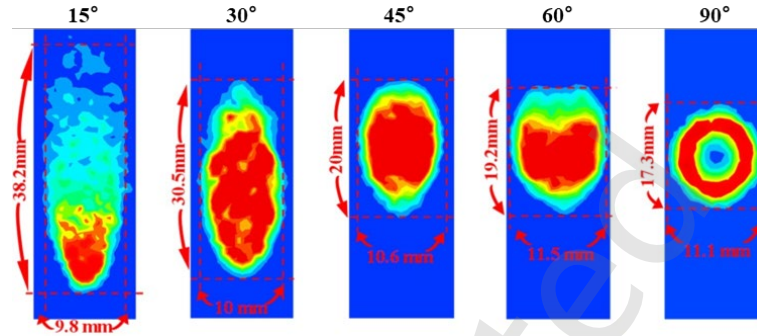


Figure 18. Simulated damage distribution under different erosion angles [56].

In conclusion, distinct geometric features play different roles in resisting erosion and cavitation. Regarding erosion resistance, sharp protrusions can alter the trajectories of solid particles, thereby reducing their direct impact on the material surface and consequently lowering the erosion rate. In contrast, for cavitation erosion resistance, micro-pit structures can modify the local flow conditions, mitigating the shock forces generated by the collapse of cavitation bubbles accumulated near the material surface. Furthermore, specifically engineered textures, such as grooved structures with optimized angular orientations, can simultaneously enhance both particle erosion and cavitation erosion resistance by improving the hydrodynamic characteristics and reducing the surface damage induced by both degradation mechanisms.

5.2 Impact of mechanical properties: Hardness, toughness, and residual stress

The mechanical properties of materials, including hardness, toughness, and residual stress, play crucial roles in determining their particle erosion and cavitation erosion resistance.

5.2.1 Hardness: A dominant factor in particle erosion and cavitation erosion resistance

Hardness, often enhanced through surface modification or work hardening, is a key factor influencing resistance. Harsha and Bhaskar [129] observed that the hardness of ferrous and non-ferrous materials increased due to work hardening after erosion tests,

with surface hardness after erosion being considerably higher than the initial hardness, indicating substantial subsurface strain hardening. Their study also highlighted that the erosion rate (ER) is dependent on dynamic hardness (H) and critical strain to failure (ϵ_c) according to Hutchings' erosion model, emphasizing the dominant role of surface hardening in erosion resistance. Similarly, Abedini et al. [130] found that ground surfaces exhibited higher hardness than polished surfaces for both NAB alloy and 316L stainless steel, attributed to plastic deformation and work hardening during grinding, which resulted in lower cavitation erosion mass loss. For 316L, the hardness of the ground sample was more than twice that of the polished sample [130]. Singh et al. [95] reported that laser textured VC surfaces showed higher microhardness and an increased hardness-to-elastic modulus (H/E) ratio, contributing significantly to improved slurry and cavitation erosion resistance. Additionally, Li et al. [131] noted that Inconel 625, with a Vickers hardness of 349.3 HV_{0.1}, exhibited a mean depth of erosion (MDE) of approximately 5.6 μm after 660 min of cavitation erosion, which was about 1/3 that of 316L stainless steel and 1/4 that of Inconel 601, directly correlating higher hardness with superior cavitation erosion resistance.

5.2.2 Toughness: The synergy between strength and toughness

Toughness and the synergy between strength and toughness are equally important, as high hardness alone may lead to brittleness. Ma et al. [132] prepared TiZrN coatings on Ti-6Al-4V alloy and found that the TiZrN/TiZr multilayer coating presented median microhardness but improved toughness compared to monolayer coatings, with scratch tests showing coating toughness in the order of M22 multilayer > thick S20 monolayer > thin S10 monolayer. This improved toughness, combined with hardness, contributed to enhanced erosion resistance under high-impact angle solid-particle erosion, reducing erosion volume to 1/178 compared to the uncoated substrate [132]. Li et al. [133] revealed that nano-bainitic steel demonstrated outstanding resistance to cavitation erosion, which stemmed from its distinctive blend of high strength and toughness. After 840 minutes of testing, it exhibited a maximum depth of erosion (MDE) of

approximately 2.20 μm , which was merely 1/15 and 1/2 of the values observed for annealed steel and martensitic steel, respectively. The microstructure of nano-bainitic steel, comprising ultrafine bainitic ferrite laths and retained austenite films, managed to preserve good toughness while attaining high strength, thereby overcoming the conventional trade-off between strength and toughness. Zhou et al. [134] utilized laser shock peening (LSP) to fabricate a bimodal grain structure on the NAB surface, where the interweaving of micron-sized and ultrafine grains synergized strength and toughness, improving cavitation erosion resistance by approximately 2.18 times compared to the matrix.

5.2.3 Grain refinement: Enhancing mechanical properties and resistance

Grain refinement, often induced by surface modification techniques, enhances mechanical properties and resistance. The bimodal grain structure formed by LSP, with a large number of micron-sized grains interwoven with ultrafine grains, enhanced the strong plasticity of the material surface. The multilayer TiZrN/TiZr coating, with finer columnar crystal size, hindered crack propagation, contributing to improved erosion resistance. Cavitation erosion induced slight grain refinement near the eroded surface of Inconel 625, with the average grain diameter near the eroded region being 8.6 μm compared to 9.2 μm away from the eroded surface [131]. Nano-bainitic steel's unique nanoscale microstructure further exemplifies how grain refinement contributes to superior mechanical properties and resistance.

5.2.4 Compressive residual stresses: Contributing to surface strengthening

Compressive residual stresses, generated through surface modification processes, also play a role in surface strengthening. The formation of compressive residual stresses and grain refinement in the TiZrN/TiZr coating was implicitly related to the gradient structures and multilayer design. Residual compressive stresses induced by LSP contributed to surface strengthening of NAB. Li et al. [114] revealed that ultrasonic surface rolling generated beneficial residual compressive stresses (RCS) on the material surface, which effectively enhanced the material's fatigue performance, with shock

waves from bubble collapse contributing to material strengthening. These residual stresses, combined with other mechanical property enhancements, collectively improve particle erosion and cavitation erosion resistance.

5.3 Interactions with fluid flow, particle size, and impact angle

Erosion and cavitation mechanisms on micro-textured surfaces are strongly influenced by fluid flow characteristics, particle properties (size, velocity), and impact angles.

5.3.1 Particle erosion on micro-textured surfaces

For particle-induced erosion, direct impingement (DI) testing using 75 μm and 300 μm silica particles at velocities of 15, 30, and 45 m/s across multiple impact angles has shown that particle size and velocity critically determine erosion behavior of materials like steel and cobalt-based alloys (Stellite) [135]. Smaller particles (75 μm) cause significantly less deformation erosion at low impact velocities compared to larger particles (300 μm), with erosion behavior varying by impact angle—coating materials such as Stellite exhibit mixed ductile and brittle responses depending on particle size and angle. Under submerged conditions, smaller particles experience greater hydrodynamic drag and turbulence, reducing impact velocity and altering effective impact angles, which are relatively low due to drag, thereby significantly affecting erosion rates on micro-textured surfaces. CFD with Lagrangian particle tracking has been used to model these particle trajectories, velocities, and impact angles, enabling accurate prediction of erosion profiles that consider fluid flow-particle-surface interactions (Figure 19) [81]. Similarly, in liquid-solid high shear flows, particle size strongly affects erosion rates: Erosion increases rapidly with particle size from 0.05 mm to 0.15 mm but slows beyond 0.15 mm due to competing effects of increased impact energy per particle and decreased impact number [136]. Impact angle also modulates erosion by influencing fluid separation and vortex formation within surface defects; for example, V-shaped defects induce more complex turbulent flows and higher erosion rates than circular defects due to stronger micro-turbulence and chaotic particle

movement.

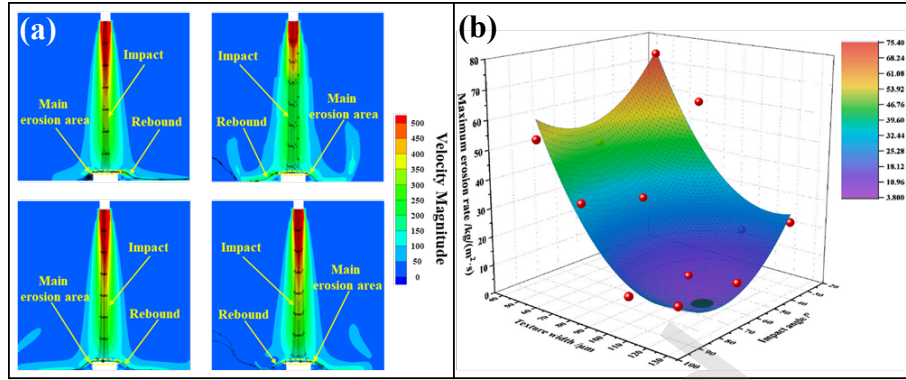


Figure 19. (a) Velocity magnitude cloud maps and particle trajectories on textured surfaces; (b) predictive models for impact angle, texture width, and maximum erosion rate [81].

5.3.2 Cavitation erosion on micro-textured surfaces

For cavitation erosion, fluid flow characteristics such as gap width and acoustic pressure waves play critical roles. Du et al. [137] developed a numerical model capturing cavity evolution and pressure pulsation, revealing that cavitation erosion correlates with flow-induced pressure pulsations and bubble dynamics, influenced by gap size, bubble number density, and acoustic field parameters. The cavity characteristics are gap-dependent, with a 1.0 mm gap height resulting in the most serious cavitation erosion, and the erosion area is determined by the maximum bubble number density on the surface. In ultrasonic cavitation, the acoustic field superposes pressure waves that affect bubble growth and collapse, with the interphase mass transfer rate (source term) depending on vapor volume fraction, bubble radius, and pressure difference influenced by the acoustic field. Experimental and numerical studies on ultrasonic horn devices confirmed that flow aggressiveness and cavitation dynamics depend on the gap width between the horn and specimen: pressure measurements showed declining aggressiveness with increasing gap width, correlating with erosion incubation times [138]. Local maximum erosion occurs at a gap width of 0.5 mm, with ring-shaped erosion patterns forming on surfaces as gap width changes from 0.05 mm to 1.5 mm [139]. CFD simulations linked these patterns to harmonic and subharmonic bubble collapses in the gap, illustrating micro-scale flow phenomena directly influencing erosion. Further, Dular et al. [140] observed that cavitation dynamics

transition with gap size: at small gaps, large, squeezed bubbles collapse slowly from both sides, while larger gaps (> 1 mm) exhibit multiple spherical cavitation clouds collapsing independently, leading to more severe erosion due to reduced shock wave shielding. In ultrasonic-assisted abrasive water jet (AWJ) systems, cavitation evolution depends on fluid pressure and turbulence at the impacted zone, with jet velocity, vibration amplitude, and frequency affecting cavitation extent—lower jet velocity and higher amplitude enhance cavitation, while higher frequency reduces it. The synergetic erosion of microjets and accelerated particles from collapsing bubbles under vibration conditions increased the material removal rate by up to 82% [141].

5.3.3 Modulating fluid-particle-surface interactions via micro-texture

Micro-texture geometry also influences fluid-particle-surface interactions. Zhang et al. [142] established a numerical model based on Lennard-Jones interatomic potential and Hamaker summation, showing that sphere-shaped textures reduce pull-off force more effectively than cylinder or cube-shaped textures (fixed coverage area ratio, height, and interval). Texture density, maximum height, and radius affect interaction forces: larger height (fixed radius) or optimal radius/height (fixed height-diameter ratio) minimizes pull-off force. These findings on texture parameter effects on interaction forces provide fundamental insights into how micro-textured surfaces modulate fluid flow and particle impingement mechanisms.

6. Experimental techniques and characterization methods for evaluating surface performance

Accurate evaluation of the particle erosion and cavitation erosion resistance of textured surfaces necessitates the organic integration of standardized testing methods, surface characterization techniques, and computational validation approaches. Unlike flat surfaces, the geometric features of textured surfaces (e.g., groove depth, pit dimensions, and spacing) impose specific requirements on the acquisition and interpretation of test results, thereby demanding particular care in the selection of methods and the setting of test parameters.

6.1 Erosion testing methods

Slurry erosion testing serves as the most direct approach for evaluating the particle impact resistance of textured surfaces, primarily following ASTM G-73 (liquid impingement erosion) and ASTM G-76 (gas jet erosion) standards. By varying parameters such as impingement angle (typically 15° – 90°), jet velocity (10–50 m/s), particle concentration (5–30 wt.%), and particle size (50–600 μm), the influence of texture geometry on erosion rate can be systematically investigated [84]. For laser-textured stainless steel surfaces, ASTM G-136 is commonly adopted, with typical conditions including $\sim 300\text{ }\mu\text{m}$ SiO_2 particles, $\sim 30\text{ m/s}$ impact velocity, and a 120 min test duration [88]. However, for textured surfaces, the mass loss method may underestimate the actual material removal due to particle entrapment within grooves, necessitating correction via three-dimensional profilometry.

Three-body abrasion tests (e.g., Korea-Tech T-3) simulate abrasive wear environments closer to real service conditions by allowing abrasive particles to freely roll between two surfaces. Typical parameters include Al_2O_3 abrasives (1.6 mm diameter, #16 mesh), a container rotation speed of 60 rpm, and a test duration of 3 h, with mass loss measured using a precision electronic balance (accuracy: 0.1 mg) [100]. This method is particularly suitable for assessing the long-term abrasion resistance of textured surfaces in particulate environments; however, it should be noted that stress concentration at texture edges may induce localized accelerated wear, requiring failure mode analysis in conjunction with SEM.

To decouple erosion, corrosion, and their synergistic effects, rotating stirring systems are widely employed, conducting tests under deionized water + sand (pure erosion), artificial seawater (pure corrosion), and a mixture of both (combined action) conditions. The synergy component is quantified by comparing the total damage with the sum of individual damages [143]. Slurry pot tests have also been utilized to validate coupled erosion–corrosion models, allowing independent adjustment of particle concentration and size [60].

6.2 Cavitation testing methods

Ultrasonic cavitation testing, conducted in accordance with ASTM G32, represents the most widely employed laboratory method for evaluating cavitation erosion resistance (Figure 20). Tests are typically performed using an ultrasonic fatigue testing machine (e.g., USF-2000, 20 ± 0.2 kHz, 50 ± 0.6 μm peak-to-peak amplitude) or an ultrasonic vibratory oscillator (e.g., Sonics VCX750, 2.31 W/cm², 50 ± 5 μm) under the stationary specimen configuration, with mass loss measured at 30-min intervals (accuracy: 0.1 mg) [26,38]. For carbon fiber reinforced polymer (CFRP) composites, cavitation clouds are generated via an ultrasonic transducer following ASTM G32-16, combined with periodic mass loss measurements and microscopic observation [144]. This method offers excellent controllability and reproducibility; however, it should be noted that pits on textured surfaces may act as cavitation bubble traps, altering the local cavitation intensity distribution. Consequently, the mass loss method should be complemented by surface topography analysis.

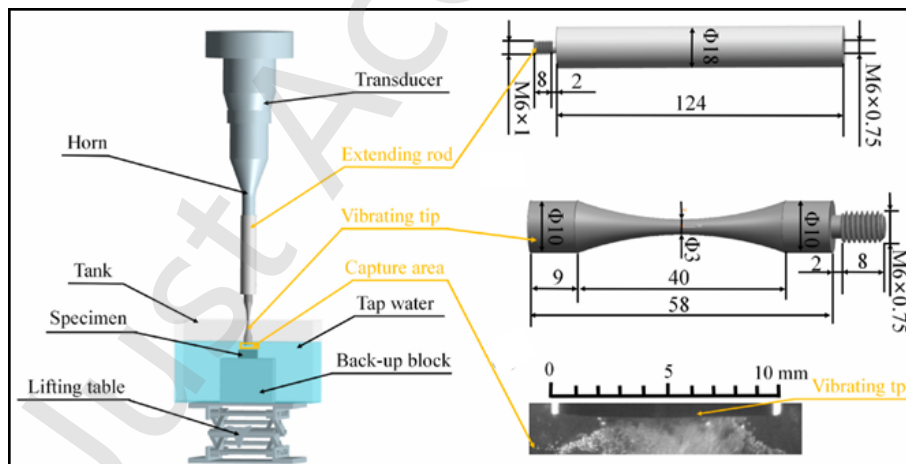


Figure 20. Schematic diagram of the ASTM G-73 testing apparatus [26].

In addition to the ultrasonic approach, jet cavitation (e.g., the Venturi tube method per ASTM G134) and rotating disc cavitation (e.g., the rotating disc method per ASTM G134) have also been employed to assess the cavitation erosion resistance of large-area textured surfaces. These methods more closely replicate the actual cavitation environments encountered in hydraulic machinery, although they exhibit a lower degree of standardization compared to the ultrasonic technique.

6.3 In-situ and advanced monitoring techniques

Conventional "post-test characterization" approaches are inherently limited in capturing the dynamic processes of erosion and cavitation. In recent years, a range of in-situ techniques have been introduced to address this limitation, as shown in Table 3.

Table 3. Principles and Information Obtained from In-situ Techniques

Technique	Principle	Information Obtained
High-speed photography	High-speed cameras (>10,000 fps) record bubble growth and collapse processes	Bubble dynamics; correlation between collapse locations and texture features
Acoustic emission (AE) monitoring	Captures elastic waves generated by material deformation/fracture	Real-time damage accumulation; crack initiation timing
Digital image correlation (DIC)	Tracks displacement fields of surface speckle patterns	Surface strain distribution; stress concentration at texture edges
Electrical resistance/wire mesh sensors	Monitors resistance changes or mass loss of metal wire mesh	Real-time erosion rate; particle impact frequency [54]

The integration of these techniques with CFD-DEM simulations enables multi-scale correlation from macroscopic damage to underlying microscopic mechanisms.

6.4 Surface characterization methods

Surface characterization aims to elucidate the damage mechanisms on textured surfaces following erosion/cavitation, rather than merely quantifying the extent of damage, as shown in Table 4.

Table 4. Surface characterization techniques

Technique	Key Information	Special Considerations for Textured Surfaces
SEM/FESEM	Wear morphologies including plowing, micro-cutting, pit formation, and particle pull-out [95]	Sample tilting is required to observe damage within grooves
EDS	Elemental distribution (e.g., F, C, O mapping in PTFE coatings) [95]	Can analyze elemental segregation at texture edges
Confocal microscopy	3D surface topography, average roughness (5 random areas) [145]	Most suitable for quantitative roughness assessment of textured surfaces
TEM	Dislocation behavior, grain refinement	Suitable for analyzing subsurface work-hardened layers
EBSD (KAM/GND)	Local strain quantification [26]	Can reveal strain concentration zones at texture edges
Micro-CT	Internal damage in CFRP (fiber debonding, tunneling effects)	The only non-destructive method for evaluating internal damage of textured surfaces
XRD	Phase identification, residual stress analysis	Assesses residual compressive stresses introduced by texturing processes [38]

6.5 Mechanical properties and wettability assessment

For textured surfaces, contact angle measurements exhibit anisotropy and should therefore be performed in multiple directions. Furthermore, the applicability of the

Wenzel and Cassie–Baxter models depends on the ratio of texture feature size to droplet size. The commonly employed testing methods are summarized in Table 5.

Table 5. Mechanical properties and wettability testing methods

Property	Testing Method	Typical Parameters	Correlation with Erosion Resistance
Microhardness	Vickers hardness tester	500 g / 15 s, 300 g / 10 s; variable load method for work hardening assessment [26]	Higher hardness↑ → Enhanced resistance to micro-cutting↑
Shore hardness	Type D durometer (ASTM D2240)	Applicable to composites such as CFRP [144]	Reflects the matrix resistance to deformation
Wettability	Contact angle goniometer	Static water contact angle (CA); textured surfaces typically exhibit CA > 90° (hydrophobic), explicable via Wenzel/Cassie–Baxter models	Higher hydrophobicity↑ → Enhanced cavitation erosion resistance (air cushion effect)↑

In summary, evaluating the particle erosion and cavitation erosion resistance of textured surfaces necessitates a multi-method, multi-scale integrated strategy.

7. Applications, challenges, and future directions in surface texturing for particle erosion and cavitation erosion resistance

Current industry applications of surface texturing for particle erosion and cavitation erosion resistance span aerospace, marine, and hydraulic machinery sectors. In aerospace, LST offers flexibility and scalability for functionalizing surfaces to enhance tribological properties, corrosion resistance, and wear performance, addressing critical needs in components exposed to harsh operational conditions [82]. Marine applications have seen significant advancements, including superhydrophobic titanium alloy surfaces fabricated via laser-heat hybrid treatment, which exhibit 18% improved erosion-corrosion resistance in simulated marine environments by reducing solid-liquid contact area [92]. For marine-grade stainless steel, a combinatorial approach of stationary friction processing (SFP) followed by micro-imprinting texturing has achieved 6-7 times greater cavitation erosion-corrosion resistance compared to as-cast samples, demonstrating potential for offshore equipment [120]. AM, particularly laser-powder bed fusion, has enabled precise micro-texturing on 17-4PH stainless steel, with rectangular pocket-shaped textures showing 7-8 times higher cavitation erosion resistance, suitable for large-area protection in marine and hydraulic environments [38]. Additionally, laser-textured VC coatings with a PTFE topcoat on SS316 steel have

shown enhanced slurry and cavitation erosion resistance, attributed to improved microhardness and reduced abrasive particle adhesion [95]. In hydraulic machinery, inverse design strategies for hydrofoil cascades with smoothed pressure recoveries at cavity closure have mitigated cavitation erosion without compromising hydrodynamic performance, providing practical solutions for pumps and turbines [24]. Textured 17-4PH stainless steel with optimized rectangular array grooves (e.g., groove width 700 μm , spacing 400 μm) has demonstrated superior cavitation erosion resistance via altered bubble collapse dynamics, offering scalable laser-processing methods for hydraulic components [31,65]. Predictive models integrating cavitation and particle erosion, such as the coupled Grant-Tabakoff model implemented in CFD solvers, have been validated to assist in optimizing component durability under harsh erosive conditions [60].

Despite these advancements, key challenges remain in evaluation strategies, durability, scalability, and theoretical understanding. In terms of evaluation strategies, in-situ monitoring techniques (high-speed photography, AE, and DIC) should be deeply coupled with CFD-DEM simulations, while standardized testing protocols specifically tailored for textured surfaces need to be developed to eliminate the interference of geometric features on measurement outcomes. Durability issues include long-term stability of textured surfaces, crack formation around laser-textured grooves due to stress concentrations and thermal cycling, and brittle fracture of certain texture designs (e.g., linear channel micro-textures in AM samples). Scalability is hindered by limitations in large-area fabrication of biomimetic anti-erosion materials, high capital costs and long processing times of laser texturing, and the need for industrial-scale optimization of processing parameters. Theoretically, gaps persist in understanding nonlinear superposition effects between erosion and applied stress, stress concentration at geometric discontinuities [121], and the dynamic mechanisms of shock wave generation during cavitation bubble collapse [114], as well as incomplete knowledge of laser ablation regimes and their impact on surface chemistry and topography.

Emerging research prospects emphasize integrated surface engineering solutions.

Morphology-material coupled biomimetic surfaces, combining grooves/bumps with soft-hard multilayer coatings, have shown exceptional erosion resistance through scalable fabrication via wire electrical discharge machining and electroplating [18]. Synergistic approaches like SFP surface deformation with micro-imprinting offer cost-effective, scalable pathways for industrial applications. AM-enabled micro-texturing provides precise control over surface topography to enhance multi-functional resistance, while laser texturing combined with complementary treatments (e.g., PTFE topcoats) improves durability. Advanced modeling and simulation, including multi-physics coupling, predictive erosion models, and inverse design algorithms, are critical for optimizing texture geometries and material interactions. Mechanistic studies into nanoscale effects, such as cavitation-induced precipitates in Inconel 625 [131], and quantitative optimization of groove parameters (e.g., width-to-spacing ratio) further guide the development of robust, application-specific surface texturing strategies.

With the rapid advancement of machine learning (ML) and artificial intelligence (AI) technologies, substantial application potential has been demonstrated in the inverse design and optimization of surface texturing [146,147]. By aggregating extensive datasets comprising surface texture design parameters and corresponding erosion- and cavitation-resistance performance metrics, data-driven models constructed via ML algorithms can rapidly predict the performance of diverse texture configurations, thereby enabling inverse design—namely, the swift generation of optimal surface texture designs tailored to specified damage-resistance performance targets. Furthermore, AI techniques can be integrated with multiphysics simulations to achieve real-time optimization of surface textures, enhancing both design efficiency and accuracy. Looking ahead, with the continuous growth of data availability and the ongoing refinement of algorithms, ML/AI is poised to become an indispensable tool for surface texture design, propelling the field toward greater intelligence and precision.

8. Conclusions

Particle erosion and cavitation erosion resistance of textured surfaces is governed

by the synergistic interaction among particle-surface impact mechanics, bubble collapse dynamics, and surface morphology-induced flow modifications. The key conclusions are summarized as follows:

(1) Multiphysics coupling is indispensable. Neither erosion nor cavitation can be adequately described by isolated mechanisms. The integration of CFD-Lagrangian particle tracking with cavitation bubble dynamics models, anchored by dimensionless mass transfer parameters, constitutes the most reliable predictive framework. Future efforts should prioritize closed-loop coupling between texture geometry, fluid micro-turbulence, and bubble collapse behavior within unified multiscale simulations.

(2) Texture geometry dictates performance more than texture existence. The mitigation efficacy is not simply a binary outcome of "textured vs. smooth" but is exquisitely sensitive to groove shape, spacing, scale hierarchy, and pattern distribution—all of which modulate local impingement angles, trap cavitation bubbles, and redirect particle trajectories. Design rules must therefore be geometry-specific rather than generic.

(3) Morphology-material synergy outperforms either strategy alone. Surface texturing alone provides limited durability; its true potential is unlocked when coupled with compressive residual stresses (e.g., shot peening, ultrasonic rolling), hard coatings (e.g., HVOF composites), or wettability engineering. Biomimetic multilayer systems that replicate natural erosion-resistant morphologies represent a particularly promising direction for scalable solutions.

(4) Scalability and long-term durability remain the critical bottlenecks. While laser texturing and additive manufacturing offer precision, they face challenges in large-area throughput and surface finish. Mechanical and hybrid treatments are more industrially viable but lack fine geometric control. Bridging this gap through hybrid fabrication workflows and predictive texture design is the most urgent research need.

In summary, the field has matured from empirical texture optimization toward mechanism-driven, morphology-material co-design. Continued interdisciplinary

convergence—uniting advanced simulation, precision manufacturing, and novel material systems—will be essential to deliver textured surfaces capable of withstanding the coupled erosion-cavitation challenges in aerospace, marine, and hydraulic applications.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix

Nomenclature			
Abbreviations			
CFD	Computational fluid dynamics	CE	Cavitation erosion
DEM	Discrete element modeling	SP	Shot peening
UDF	User-defined functions	SDB	Slide diamond burnishing
DIC	Digital image correlation	USR	Ultrasonic surface rolling
RANS	Reynolds-averaged Navier-Stokes	HVOF	High-velocity oxy-fuel
SST	Shear-stress transport	TAZ	Thermal altered zone
DCM	Density-correction methods	SFP	Stationary friction processing
DPM	Discrete phase model	LSP	Laser shock peening
DRW	Discrete random walk	RCS	Residual compressive stresses
VOF	Volume-of-fluid	AWJ	Abrasive water jet
DDPM	Dense discrete phase models	SEM	Scanning electron microscopy

DOF	Degree of freedom	EDS	Energy dispersive spectroscopy
RSM	Response surface methodology	TEM	Transmission electron microscopy
PIV	Particle image velocimetry	EBSD	Electron backscatter diffraction
LST	Laser surface texturing	KAM	Kernel average misorientation
VC	Vanadium carbide	GND	Geometrically necessary dislocation
CA	Contact angle	XRD	X-ray diffraction
AM	Additive manufacturing	CFRP	Carbon fiber reinforced polymer
NAB	Nickel-aluminum bronze	AE	Acoustic emission
ML	Machine learning	AI	Artificial intelligence
Symbols			
ER	Erosion rate	u	Instantaneous fluid velocity
m_p	Particle mass	V_{th}	Velocity
v_p	Particle impact velocity	C_d	Discharge coefficient
p	Plastic flow stress	Re	Reynolds number
n	Particle velocity exponent	β	Area ratio
α	Particle incidence angle	L_c	Cavitation length
α_o	Critical incidence angle	V_c	Cavitation volume
φ	Shear deformation energy	W/H	Width/height
ε	Cutting deformation energy	L/H	Length/height
K	Empirical constant	t_c	Bubble collapse
F_s	Particle shape factor	E	Young's modulus
K_p	Particle shape and hardness factor	I_A	Acoustic intensity
d_p	Particle diameter	S_A	Ultrasound emitting surface area
f_v	Mass fraction of steam	c_p	Specific heat
f_g	Mass fraction of non-condensable gas	dT/dt	Temperature change rate
Γ	Diffusion coefficient	L/W	Width-to-spacing ratio
P_v	Saturated vapor pressure	H	Dynamic hardness
R_B	Bubble diameter	ε_c	Critical strain to failure
ρ	Density	H/E	Hardness-to-elastic modulus
σ	Cavitation number	τ	Volume fraction
P_e	Downstream pressure	N_{tot}	Total number of time steps
P_v	Liquid vapor pressure	$-da/dt$	negative time gradient

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Ning Wang is currently a Ph.D. candidate in the School of Mechanical Engineering at the University of Science and Technology Beijing. He earned his Bachelor's degree in Mechanical Engineering from Shenyang Aerospace University in China in 2020 and obtained his Master's degree from Inner Mongolia University in China in 2024. His research focuses on surface texture design, theoretical research on erosive and cavitation wear, as well as computational fluid dynamics analysis.



Ping Chen is currently a professor in the School of Mechanical Engineering at University of Science and Technology Beijing. She received her Bachelor's degree in Mechanical Design and Theory from Hunan University of Science and Technology in 1995, Master's degree from Henan Polytechnic University in 2002, and Ph. D. degree from China University of Mining and Technology Beijing in 2008. Her research interests lie in the design and performance optimization of bionic surface microstructures, as well as multidisciplinary-field coupled modeling, simulation, and optimization design. She is a member of China Graphics Society.



Xueqi Ye is currently a Ph.D. candidate in the School of Mechanical Engineering at the University of Science and Technology Beijing. She earned her Bachelor's degree in Mechanical Engineering from Yanshan University in China in 2022 and is expected to obtain her Master's degree from the University of Science and Technology Beijing in 2025. Her research focuses on the design and performance optimization of bionic surface microstructures.



Yi Zhang currently serves as a Distinguished Associate Professor in the School of Mechanical Engineering at the University of Science and Technology Beijing. He earned his Bachelor's degree in Mechanical Engineering from Nanchang University in China in 2014. Subsequently, he obtained his Master's degree in 2018 and his Ph.D. degree in 2022 from Hefei University of Technology in China. His research interests are diverse, encompassing multidisciplinary coupled modeling, simulation, and optimization design, as well as the science and technology of surfaces and interfaces in high-end equipment.



Weixu Yang is currently an associate professor in the School of Mechanical Engineering at University of Science and Technology Beijing. She received her Bachelor's degree in Mechanical Engineering from Chang'an University, China, in 2013, and the Ph.D. degree from Beijing Institute of Technology, China, in 2019. Her research interests include microscale adhesive contact mechanics and surface micro/nano textures design in triboelectric nanogenerator.