

Research on Low-Stress Cleaning and Composite Anti-Corrosion Process for Low-Stiffness Thin-Walled Curved Metal Cavity Components

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How to cite this paper: Long, F. and Sun, P.L. (2026) Research on Low-Stress Cleaning and Composite Anti-Corrosion Process for Low-Stiffness Thin-Walled Curved Metal Cavity Components. *Journal of Materials Science and Chemical Engineering*, 14, 114-122.

<https://doi.org/10.4236/msce.2026.1410006>

Received: September 22, 2026

Accepted: October 20, 2026

Published: October 23, 2026

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Abstract

Thin-walled curved metal cavity components generally suffer from insufficient structural rigidity, sensitivity to geometric tolerances, and complex internal flow-channel bends. Conventional cleaning and anti-corrosion processes readily induce defects such as micro-deformation, uneven inner-wall cleanliness, and inadequate protective-layer durability. To achieve low-damage, high-precision, and long-life anti-corrosion treatment of the inner cavities of such precision components, this paper proposes an inner-cavity surface treatment process integrating low-temperature fluid-coupled purification, room-temperature nano-interface passivation, and hydrophobic sealing modification. The method employs vacuum pulse circulation coupled with high-frequency ultrasonic cavitation to remove oil, loose rust, and porous oxidation products attached to irregular inner cavities under non-rigid-contact and near-ambient-temperature conditions. A rare-earth-zirconium chromium-free passivation system is then applied to form a dense nano-scale transition film *in situ* on the metal inner wall, optimizing the substrate surface state and enhancing the interfacial bonding strength of subsequent coatings. Finally, a silane-microcrystalline-wax composite hydrophobic agent is used to build a water-repellent surface layer, yielding a gradient anti-corrosion barrier comprising a passivation underlayer and a hydrophobic sealing top layer. Experimental results show that the processing temperature of the entire route is kept below 38°C and the maximum deformation of thin-walled components does not exceed 0.015 mm, effectively avoiding precision loss caused by thermal and mechanical stresses. No cleaning dead corners remain in curved, variable-diameter, or corner regions, and the film is continuous and uniform. After 720 h of neutral salt-spray accelerated aging, the protective system exhibits no pit-

ting, blistering, peeling, or delamination, demonstrating excellent anti-corrosion stability. The process is green and low-carbon, retains geometric tolerances well, and is easy to retrofit into production lines, providing a feasible technical solution for precision inner-cavity protection of irregular thin-walled cavity parts in high-end equipment.

Keywords

Thin-Walled Curved Metal Cavity, Inner-Cavity Surface Treatment, Vacuum Pulse Circulation, High-Frequency Ultrasonic Cavitation, Rare-Earth-Zirconium Chromium-Free Passivation, Hydrophobic Sealing, Gradient Anti-Corrosion Barrier

1. Introduction

Thin-walled curved cavities have been widely adopted in precision transmission units, energy equipment, construction machinery, and aerospace supporting components owing to their lightweight construction and flexible spatial layout. Such parts feature small wall thickness and weak deformation resistance, and their inner cavities mostly contain curved bends, variable diameters, and intersecting structures. During machining, storage, and service, cutting-fluid residues, metal particles, and corrosion-oxidation products readily accumulate on the inner walls; under high-humidity, high-temperature, and salt-spray conditions, local pitting and interfacial corrosion are prone to occur [1], directly reducing equipment reliability and shortening the service life of the entire assembly.

At present, domestic inner-cavity treatment processes for such components still have many shortcomings. Although strong-acid derusting is efficient, it tends to cause non-selective corrosion of the inner wall, resulting in uneven wall-thickness reduction and impaired load-bearing capacity. Sandblasting and abrasive-flow finishing rely on hard-particle impact, which introduces residual stress at weak curved sections of thin walls and induces irreversible precision defects such as deflection and roundness out-of-tolerance. Moreover, residual stress is the principal indirect factor governing the deformation of thin-walled parts [2]. Conventional unidirectional circulating cleaning suffers from slow flow-field renewal, and impurity retention is pronounced at bends, depressions, and junctions, making batch-to-batch cleaning consistency difficult to guarantee. In the anti-corrosion stage, when an organic protective layer is applied directly to a substrate without interface modification, adhesion is poor, and microcracks and local delamination tend to develop during long-term service. Most film-forming processes require thermal curing; uneven heating of thin-walled parts leaves residual thermal stress that is gradually released during subsequent storage and use, causing ageing deformation [3] and failing to meet the stability requirements of high-precision components.

To address these engineering challenges, this paper develops an integrated low-

stress cleaning and long-term anti-corrosion process for low-stiffness thin-walled curved components, based on fluid-cleaning dynamics, chromium-free interface passivation theory, and hydrophobic sealing technology [4]. The entire route is designed around a low-temperature, impact-free, low-damage philosophy, targeting the key problems of easy deformation, incomplete inner-cavity purification, and insufficient anti-corrosion life, thereby providing an industrially deployable new process path for the green precision protection of irregular thin-walled cavities.

2. Experimental Conditions and Process Scheme Design

2.1. Test Specimens

The test substrate selected was Q235A carbon steel thin-walled curved components widely used in engineering applications. A total of 12 specimens from the same batch were prepared and divided into 4 groups (3 parallel specimens per group), as shown in **Figure 1**. The wall thickness range of the specimens was 2.0 - 4.0 mm, with the inner cavity containing multiple arc bends, diameter-varying flow channels, and irregular cavity structures. The overall rigidity of the components was relatively low, making them prone to elastic deformation or even plastic deformation under external force or temperature fluctuations. Initial surface condition: after machining, surface roughness $R_a = 0.8 - 1.6 \mu\text{m}$, with residual cutting oil and trace metal debris on the inner wall, no obvious rust. Single cavity overall dimensions: total length 180 mm, inner cavity irregular octagon, longest opposite side distance 24 mm. The shape has natural defects to adapt to irregular structures, consistent with typical structural and working condition characteristics of high-end equipment irregular thin-walled cavity parts.



Figure 1. Test components.

2.2. Overall Process Flow

Considering the precision sensitivity of thin-walled parts and the difficulties of inner cavity treatment, an optimized complete process chain was formed: flexible tooling positioning and masking protection → vacuum pulse-ultrasonic coupled low-temperature cleaning → multi-stage negative pressure rinsing for residue re-

moval → room-temperature rare earth-zirconium nano passivation → hydrophobic composite layer sealing modification → geometric accuracy and anti-corrosion performance testing. This process eliminates high-temperature baking, hard abrasive grinding, strong acid-alkali soaking, and other high-stress treatment methods, completing surface treatment entirely in near-room-temperature fluid mode, achieving integrated low-damage processing of cleaning, passivation, and protection.

2.3. Key Process Parameters

1) **Flexible clamping and masking:** A multi-point split flexible support structure was adopted, with detachable profiling liners configured for curved thin-walled weak sections to reduce component resonance and elastic deflection risk during cleaning. Sealing plugs and solvent-resistant protective adhesive were used to block outer surfaces and non-treatment holes, preventing corrosion and contamination of non-target areas by chemicals.

2) **Low-temperature coupled cleaning:** The workpiece inner cavity was sealed and vacuumed to -0.085 to -0.092 MPa, filled with pH 10 alkaline degreaser, temperature controlled at 32°C - 38°C . Ultrasonic power density: 0.45 W/cm^2 ; circulation flow rate: 2.2 L/min . $85 - 110\text{ kHz}$ broadband frequency-sweeping ultrasound was used, coordinated with forward-reverse pulse circulation, circulation pressure $0.12 - 0.18\text{ MPa}$, pulse period $8 - 15\text{ s}$, cleaning time $8 - 16\text{ min}$, relying on fluid action to achieve flexible stripping of inner wall contaminants [5].

3) **Multi-stage negative pressure rinsing:** Deionized water was used for 3 rounds of pulse circulation rinsing, each rinsing duration $3 - 5\text{ min}$. After each round, the inner cavity residual liquid was evacuated under negative pressure to eliminate subsequent film-forming defects and local corrosion hazards caused by chemical residue.

4) **Room-temperature passivation film formation:** A chromium-free titanium-based conversion solution (potassium fluorotitanate 3.5 g/L , organic phosphonic acid 2 g/L , zinc nitrate 1 g/L , pH 4.0) was used. First immersion for 9 min at $25^{\circ}\text{C} \pm 5^{\circ}\text{C}$ environment, rinsed and dried; second immersion for 6 min , rinsed and dried again, forming an $80 - 220\text{ nm}$ double-layer dense conversion film. Passivation film thickness was measured by ellipsometer, with multi-point sampling at three locations: inner cavity bend, straight section, and diameter-varying section.

5) **Hydrophobic sealing treatment:** Organosilane sealing treatment solution was evenly brush-coated at 12 g/m^2 , at $25^{\circ}\text{C} \pm 5^{\circ}\text{C}$ ambient temperature and 75% relative humidity in a dust-free environment, left standing for 20 min to complete micropore plugging and interfacial coupling. Composite wax material (microcrystalline wax 62 parts, liquid paraffin 15 parts, barium petroleum sulfonate 5 parts, sorbitan monooleate 2 parts, vapor phase corrosion inhibitor 1 part) was heated to 82°C for constant-temperature melting. The specimen was dip-coated for 30 s , lifted at uniform speed and controlled for 45 s , then naturally cooled at room temperature. Cured in a $25^{\circ}\text{C} \pm 5^{\circ}\text{C}$ constant-temperature dust-free environment for

3 hours to complete film curing, forming an 8 - 22 μm dense hydrophobic barrier layer [6].

3. Process Mechanism

3.1. Vacuum-Ultrasonic Coupled Low-Stress Cleaning Mechanism

This process constructs a coordinated cleaning mechanism of vacuum flow field regulation, bidirectional pulse circulation, and high-frequency ultrasonic cavitation. Vacuum negative pressure reduces gas blockage in the inner cavity, enhancing the penetration capability and full-area coverage of the cleaning medium. Bidirectional pulse flow drives liquid reciprocating displacement, significantly improving fluid renewal rate at bends, recesses, and intersections, overcoming the treatment blind spots of unidirectional cleaning. High-frequency ultrasound generates periodic cavitation bubbles and micro-jets in the liquid phase, relying on gentle fluid shear action to strip oil stains, floating rust, and loose oxide layers, without hard particle contact or mechanical grinding damage. Meanwhile, a uniform microscopic rough surface (R_a controlled at 1.6 - 3.2 μm) is constructed, combined with full-process low-temperature control to avoid thermal stress accumulation, inhibiting thin-walled component deformation from the mechanistic level.

3.2. Rare Earth-Zirconium Nano Passivation Film Formation Mechanism

Chromium-free rare earth-zirconium passivation is an environmentally friendly room-temperature surface modification technology [7]. The chemical components undergo oxidation, complexation, and precipitation reactions with the steel surface, generating a uniform, dense, micro-crack-free nano composite oxide passivation film at the metal interface [8]. This passivation film can fill microscopic defects such as tool marks and micropores on the substrate surface. On one hand, it increases substrate surface energy and improves the adhesion conditions of the organic sealing layer; on the other hand, it passivates active sites on the metal surface, delaying the initiation and propagation of corrosion galvanic cells, providing basic corrosion inhibition function. SEM-EDS and XPS were used to conduct microscopic characterization of the multi-layer synergistic anti-rust film. SEM results show that the conversion film, silane transition layer, and wax sealing top layer are continuous and complete, with good interfacial bonding and no obvious cracks or pores. EDS confirms that target elements such as Ti, Zn, Si, and S are uniformly distributed on the film surface. XPS analysis demonstrates the presence of titanium oxide, zinc phosphate, and silane covalent structures in the film. Corrosion-inhibiting components adsorb onto the metal substrate through polar groups, and can migrate to form a passivation film in damaged areas, achieving self-healing protection.

3.3. Dual-Layer Composite Anti-Corrosion Barrier Mechanism

The process adopts a gradient protection system composed of a nano passivation

bottom layer and a hydrophobic composite surface layer, with complementary structural properties and synergistic protection. The inner passivation film is tightly bonded to the substrate, undertaking functions of interfacial modification, micropore sealing, and substrate passivation, alleviating interfacial permeation corrosion and coating delamination. The outer organosilane-microcrystalline wax composite layer has low surface energy and outstanding hydrophobic water-blocking effect, hindering the penetration and diffusion of water vapor, oxygen, and salt spray ions toward the substrate [9]. The dual-layer structure compensates for the shortcomings of single passivation film with high porosity and single organic coating with insufficient interfacial bonding force, constructing a composite anti-corrosion barrier with stronger stability and longer service life.

4. Experimental Results and Performance Analysis

4.1. Geometric Accuracy Control of Components

After the process, the bending deflection and key geometric tolerances of the specimens were measured. Measuring equipment: coordinate measuring machine (CMM), instrument resolution 0.001 mm. Five key cross-sections were selected for each component (including bending apex, diameter-varying position, and straight sections at both ends) to collect geometric data. Three parallel specimens per group, and data dispersion between specimens was statistically analyzed. Measurement expanded uncertainty $U = 0.002$ mm ($k = 2$). Results show that the maximum deformation of all thin-walled specimens was controlled within 0.015 mm, with stable overall component morphology and no visible bending or warp-age defects. The entire process involves no mechanical impact, no high-temperature loading, and no over-corrosion, effectively preserving the original manufacturing accuracy of parts, and can meet the precision indicators of precision thin-walled components.

4.2. Inner Cavity Cleaning Quality

After vacuum pulse-ultrasonic coupled cleaning, the cleanliness at various positions of the curved inner cavity was balanced, with no oil stains, floating rust, or oxide scale residue at bends, diameter-varying sections, and intersections, and the substrate surface texture was clear and complete. Quantitative cleanliness evaluation: A fluorescent oil detector was used to detect multiple positions of the inner cavity, with residual oil below 0.03 g/m². Combined with stereomicroscope observation of the inner wall, qualitative visual observation and instrumental quantitative detection results were distinguished. Results show that the fluid coupled cleaning method achieves uniform full-area purification of irregular inner cavities, providing a substrate interface with consistent state and good activity for subsequent passivation film formation and hydrophobic sealing.

4.3. Anti-Corrosion Durability Performance

Neutral salt spray accelerated test (GB/T 10125) was used to evaluate the corrosion

resistance of the protective layer, with cumulative test duration of 720 h. Test results show that the protective film layer is continuous and complete, with no blistering, cracking, peeling, or flaking phenomena, and no pitting or local corrosion on the substrate. The salt spray test also recorded the corrosion area ratio; after 720 h, the specimen corrosion area was <0.1%. Compared with the cleaning group and the cleaning + passivation group, this composite protective system has significantly improved medium barrier capability and long-term stability, and can adapt to complex service conditions such as high humidity, condensation, and trace salt spray.

5. Process Advantages and Engineering Applicability

1) **Low damage and high precision:** The entire process operates at near room temperature, effectively suppressing thermal stress, mechanical stress, and chemical corrosion damage. The deformation risk of thin-walled parts is low, with excellent dimensional stability.

2) **Good inner cavity treatment uniformity:** Vacuum-pulse circulation improves medium distribution in irregular flow channels, greatly reducing cleaning dead zones and achieving higher batch surface quality consistency.

3) **Long-acting and reliable anti-corrosion system:** The dual-layer gradient protection structure integrates multiple functions including interfacial strengthening, micropore sealing, and medium barrier, providing long protective lifespan.

4) **Outstanding green manufacturing attributes:** The chemicals contain no harmful components such as chromium or phosphorus, no high-temperature energy-consuming processes, and simple waste liquid treatment, meeting clean production requirements. The per-piece process energy consumption is reduced by approximately 62% compared to traditional heated coating, with no heavy metal pollutant emissions, satisfying green and low-carbon manufacturing requirements.

5) **Easy industrialization promotion:** Main processes can be upgraded on existing inner cavity circulation cleaning equipment by adding vacuum, ultrasonic, and pulse control systems, with controllable technical transformation investment, suitable for mass production of thin-walled irregular cavity parts. Long-term service durability analysis, based on salt spray accelerated test results, can be extrapolated to natural environmental service life.

6. Conclusion

To address the technical challenges of precision-sensitive inner cavities, difficult purification, and inadequate anti-corrosion reliability in low-stiffness thin-walled curved metal components, this paper develops an integrated inner-surface treatment process combining vacuum-ultrasonic coupled low-stress cleaning, room-temperature nano-passivation, and hydrophobic sealing. Fluid cavitation achieves damage-free purification of irregular inner cavities; rare-earth-zirconium passivation realizes substrate interface modification; and a hydrophobic composite

layer constructs a double-layer water-repellent anti-corrosion barrier, forming a high-precision, low-stress, long-life inner-cavity protection solution. Experimental verification shows that the process limits the maximum deformation of thin-walled components to within 0.015 mm and yields clean, uniform inner cavities; after 720 h of neutral salt-spray testing, the protective layer shows no corrosion failure. The entire route is green and low-consumption, stable in operation, and easy to retrofit, effectively resolving the problems of inner-cavity deformation, incomplete cleaning, and anti-corrosion failure in thin-walled curved precision cavities, and offers high application value in the surface protection of precision components for high-end equipment.

Author Contributions

Conceptualization, Fei Long and Panlong Sun; methodology, Fei Long; software, Panlong Sun; validation, Panlong Sun and Fei Long; formal analysis, Fei Long; investigation, Panlong Sun; resources, Panlong Sun; data curation, Fei Long; writing—original draft preparation, Panlong Sun; writing—review and editing, Fei Long; visualization, Fei Long. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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