

Review

Research Advancements of Wear-Resistant Coatings Fabricated on Aluminum and Its Alloys

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Abstract

The low hardness and insufficient wear resistance of aluminum and its alloys restrict their broader application in various fields. The application of surface protective coatings can effectively enhance the hardness and wear resistance of aluminum and its alloys. This article provides a comprehensive review of the recent research progress of wear-resistant coatings fabricated on aluminum and its alloys. The relevant achievements in the recent research works of preparing wear-resistant coatings by one-step methods (such as anodic oxidation, micro-arc oxidation, cold spraying, plasma spraying, and electrodeposition) and two-step methods (anodic oxidation and physical vapor deposition, micro-arc oxidation and sealing, magnetron sputtering, and plasma nitriding) are mainly introduced. The working principles of each coating preparation method, along with their impacts on the microstructure and tribological performance of the coatings, were systematically examined. Additionally, a comparative analysis was conducted to evaluate the advantages and disadvantages of each coating preparation method.

Keywords: friction; wear resistance; coating; aluminum and its alloys



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1. Introduction

The applications of aluminum and its alloys are developing in many industrial fields, ranging from aerospace to automotive, shipping, marine, construction, and packaging industries due to their favorable characteristics, such as low density, high specific strength, exceptional toughness, low cost, strong thermal and electrical conductivity, easy to manufacture, low cost, and recycling [1–3]. However, the relatively low hardness, insufficient wear resistance, and limited corrosion resistance of aluminum alloys significantly restrict their broader application [4–6].

During contact with other materials and under conditions of relative motion, the surface of aluminum is susceptible to wear [7,8]. The wear resistance of aluminum alloys is influenced by a multitude of factors, including their compositional makeup, processing techniques, and heat treatment conditions [9–11]. In recent years, there have been two predominant approaches, the alloying and application of protective coatings, to improve the hardness and wear resistance of aluminum and its alloys. The incorporation of Fe [12,13], Cr [14,15], V [16,17], Si [18], Ni [17], and Co [19] alloying elements can effectively enhance the hardness and wear resistance of aluminum and its alloys through solid solution strengthening and precipitation strengthening effects. However, the excessive incorporation of

alloying elements may potentially lead to adverse effects on other properties of aluminum alloys, such as a reduction in corrosion resistance [20]. Therefore, the application of surface protective coatings has emerged as the primary approach to enhance the hardness and wear resistance of aluminum and its alloys.

According to the process flow of the preparation technology, the methods for preparing wear resistant coatings on aluminum and its alloys can be categorized into one-step methods and two-step methods. This paper provides a comprehensive introduction to the working principles and illustrative examples of various methods for preparing wear-resistant coatings of aluminum and its alloys, along with an in-depth analysis and discussion of the factors contributing to enhanced wear resistance.

2. One-Step Methods

Currently, there exist numerous methods for fabricating wear-resistant coatings on aluminum alloys. The one-step method has garnered widespread attention due to its advantages of simplicity and high efficiency. The following section will be integrated with the actual published literature for a comprehensive summary. Table 1 presents the relevant data regarding the performance of wear-resistant coatings on aluminum and its alloys fabricated using a one-step method.

Table 1. The performance of wear-resistant coatings for aluminum and its alloys prepared by one-step methods.

One-Step Methods	Substrate			Coating				Ref.
	Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate	
AO	AA1050	-	5.3–32.9 mg	Al, Al ₂ O ₃ , Si ₃ N ₄	-	0.2	0.6–6.7 mg	[21]
		~1.16	1.5 mm ³	Al ₂ O ₃ , PTFE	14–24 µm	~0.9	0.002 mm ³	[22]
	AA2017-T4	-	-	Al ₂ O ₃ , DLC	-	0.44–0.72	-	[23]
	AA5052	1	-	Al, O	4–15 µm	0.75–1	-	[24]
	5086	1~1.4	-	Al, Al(OH) ₃ , Amorphous phase	52 ± 1 µm	0.73 ± 0.13	6.7 × 10 ⁻⁴ mm ³ /N·m	[25]
	6061	-	-	Al ₂ O ₃	18 µm	0.12–0.7	0.01–0.2 mm ³	[26]
MAO	Pure Al	-	-	Al ₂ O ₃ , Al, Si, Fe, O	-	0.25–0.38	2 mg	[27]
		-	-	Al, α-Al ₂ O ₃ , γ-Al ₂ O ₃ , AlPO ₄ , Na, O, C, P, Si	-	0.217–0.705	-	[28]
	1060	-	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , Si, P	5.95–7.95 µm	0.31–0.79	-	[29]
	2024	-	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , Si, P, h-BN	12.26–19.85 µm	0.4–0.6	4.3 × 10 ⁻⁴ –1 × 10 ⁻³ mm ³ /N·m	[30]
		0.3–0.5	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , AlPO ₄ , KSi ₃ Al ₃ O ₁₀ (OH) ₂	-	0.3–0.5	-	[31]
		0.88–0.9	4.5 × 10 ⁻⁴ mm ³ /N·m	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , Na, Si, K, Ca, Fe, P	180 µm	0.55–0.85	10 ⁻⁵ –10 ⁻⁷ mm ³ /N·m	[32]

Table 1. Cont.

One-Step Methods	Substrate			Coating				Ref.
	Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate	
MAO	2024-T3	0.46	1 mg	α -Al ₂ O ₃ , χ -Al ₂ O ₃ , Al _{3.21} Si _{0.47} , amorphous phase	~40 μ m	0.08	0.2 mg	[33]
	2A50	0.4	-	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , MoS ₂ , Al ₆ Si ₂ O ₁₃	20~75 μ m	0.1	5.28×10^{-4} cm ³ /N·m	[34]
		-	-	γ -Al ₂ O ₃	45 μ m	0.35~0.55	-	[35]
	5086	1~1.4	-	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , etc	58 ± 1 μ m	0.92 ± 0.06	2.7×10^{-5} mm ³ /N·m	[25]
	5754	-	-	γ -Al ₂ O ₃ , β -Al ₂ O ₃ , AlPO ₄ , Al ₂ Mo ₃ C	3.6~11.6 μ m	-	3.09×10^{-3} ~ 3.54×10^{-3} mm ³ /N·m	[36]
	6061	0.5~0.75	3.91×10^{-3} mm ³ /N·m	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , AlPO ₄	21.3 ± 2.9 μ m	0.35	4.8×10^{-5} mm ³ /N·m	[37]
		0.4~0.5	30.7~93.5 mg	Al ₆ Si ₂ O ₁₃ , α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Amorphous alumina	125 μ m	-	18.2~86.6 mg	[38]
	6063	-	-	Al ₂ O ₃ , TiO ₂ , PTFE	~31.4 μ m	0.28	$(0.92 \pm 0.23) \times 10^{-7}$ mm ³ /N·m	[39]
	6082	-	-	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , 2Al ₂ O ₃ , Al ₆ Si ₂ O ₁₃	40~113 μ m	0.75~0.83	4.75×10^{-6} ~ 4.23×10^{-5} mm ³ /N·m	[40]
	6082-T6	0.4~0.5	3.9×10^{-4} ~ 5.5×10^{-4} mm ³ /N·m	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Al ₆ Si ₂ O ₁₃	~90 μ m	0.5~0.75	9.3×10^{-6} ~ 1.6×10^{-5} mm ³ /N·m	[41]
	7075	0.1~1.4	-	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Al ₆ Si ₂ O ₁₃	58 ± 3 μ m	0.09~0.75	2.4×10^{-5} ~ 7.31×10^{-4} mm ³ /N·m	[42]
	7N01	0.4~0.6	2.07×10^{-4} g/min	α -Al ₂ O ₃ , γ -Al ₂ O ₃	3.8~9.3 μ m	0.2~0.3	2.35×10^{-5} g/min	[43]
	A356	0.46~0.74	2.94×10^{-5} mm ³ /N·m	-	28~31 μ m	0.25~0.73	4.1×10^{-7} ~ 2.59×10^{-5} mm ³ /N·m	[44]
	D16T	-	32.5 ± 2.1 mg	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , SiO ₂ , etc	60~65 μ m	0.346~0.379	7.1 ± 0.6 ~ 4.8 ± 0.3 mg	[45]
Laser methods	AlSi10Mg	0.35~0.4	2.1×10^{-3} mm ³ /N·m	γ -Al ₂ O ₃ , 3Al ₂ O ₃ ·2SiO ₂ , amorphous phases	9~13 μ m	0.2~0.5	2.1×10^{-5} ~ 3.6×10^{-4} mm ³ /N·m	[46]
	1100	-	4.85×10^{-8} g/mm	Al ₈ Mo ₃ , Al ₅ Mo, AlMo ₃ , α -Al	120~200 μ m	-	9.60×10^{-9} ~ 1.51×10^{-8} g/mm	[47]
		-	-	Ti, B, Al, Sc	-	0.4	24.8 mg/h	[48]
	6061	0.46	2.48×10^{-9} m ³	TiB ₂ , TiC, Fe ₄ Al ₁₃ , Cr ₂ B, Cr ₇ C ₃ , α -Al	-	0.25~0.32	1.8×10^{-10} m ³	[49]
	5083	-	3.5×10^{-4} mm ³ /N·m	Al, Cr, Fe, Co, Ni, Cu	-	-	6.6×10^{-7} ~ 9.4×10^{-5} mm ³ /N·m	[50]
		-	8.2 mg	Ti, TiBCN	-	0.182	2.4 mg	[51]

Table 1. Cont.

One-Step Methods	Substrate				Coating			Ref.	
	Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate		
Spraying methods	CS	2024	0.45~1.2	-	Al ₂ O ₃	~5 mm	-	6.5 mm ³ /N·m	[52]
		6061			CoCrFeMnNi	~1 mm	0.3~0.7	5.10 × 10 ⁻⁵ mm ³ /N·m	[53]
		ADC12	~1.06	8.96 × 10 ⁻⁴ mm ³ /N·m	Ni, Ti ₃ AlC ₂	500~800 μm	0.64~0.84	1.87 × 10 ⁻⁵ ~1.38 × 10 ⁻⁴ mm ³ /N·m	[54]
	PS/SPS	Al 2014	0.73	-	GNs	1.9~3.1 μm	0.06~0.17	-	[55]
		2A12	0.6 ± 0.2	5.56 × 10 ⁻² mm ³	α-Al, β-Si, Al ₉ Si, Al _{3.21} Si _{0.47} , CuAl ₂	500 μm	0.4 ± 0.06	1.56 × 10 ⁻² mm ³	[56]
		6061	0.46	8.26 × 10 ⁻³ mm ³ /N·m	α-Al, β-Si, θ-Al ₂ Cu	-	0.31	1.62 × 10 ⁻³ mm ³ /N·m	[57]
		7005	0.4~0.5	7.6~16.4 mg	83 wt.% Ni60, 15 wt.% Al ₂ O ₃ , 2 wt.% CeO ₂	-	0.15~0.3	0.7~0.9 mg	[58]
		YL113	-	-	Al-25Si-4Cu-0.9Mg	-	0.177	1.46 × 10 ⁻³ mm ³	[59]
		ZL109	-	-	TiO ₂ , TiO, Ti ₂ O ₃	~400 μm	0.05~0.09	2.1 × 10 ⁻⁶ ~3.5 × 10 ⁻⁶ mm ³ /N·m	[60]
		ZL109	0.1~0.25	-	Ni60 alloy	300 μm	0.1~0.25	6.45~14.4 mg	[61]
		Al-Si	0.60~0.81	3.31 × 10 ⁻⁴ ~5.9 × 10 ⁻⁴ g/m	ZAC	251 ± 0.07 μm	0.44~0.62	9.1 × 10 ⁻⁵ ~2 × 10 ⁻⁴ g/m	[62]
					FZA	253 ± 0.05 μm	0.36~0.47	7.8 × 10 ⁻⁵ ~9.8 × 10 ⁻⁵ g/m	
	Spray	7050	-	-	Ti ₃ AlC ₂ , PI, MPS	-	0.58	2.03 × 10 ⁻⁵ mm ³ /N·m	[63]
			-	-	PDMS, PI	-	0.07	4.8 × 10 ⁻⁷ mm ³ /N·m	[64]
Deposition methods	EP	6061	-	-	Ni, P, ZnO, Aliquat 336	-	-	~10 ⁻⁷ ~2.5 × 10 ⁻⁴ mm ³ /N·m	[65]
		A356	0.64	-	Ni, B, CeO ₂	40 μm	0.531	-	[66]
		LM24	-	4.90 × 10 ⁻¹² m ³ /N·m	Ni, P	~15 μm	-	0.52 × 10 ⁻¹² m ³ /N·m	[67]
	1060	0.85~1.25	3.1 × 10 ⁻³ mm ³ /N·m	Al ₃ C ₄ , Al ₂ O ₃ , ZrO ₂	~50 μm	~0.2	2.3 × 10 ⁻⁴ mm ³ /N·m	[68]	
				Al ₃ C ₄ , Al ₂ O ₃	~65 μm	~0.37	1.4 × 10 ⁻⁴ mm ³ /N·m		
		1100	0.5	300 μm	Co-Cr-Mo alloy	-	0.35	160 μm	[69]
	ED	2024-T6	0.29	4.73 × 10 ⁷ μm ³	Ni	25 μm	0.07	1.87 × 10 ⁷ μm ³	[70]
					Ni, GO	41.6~51.6 μm	0.06	1.48 × 10 ⁷ μm ³	
		A356	-	-	Ni, SiC	~100 ± 5 μm	0.527	1.63 × 10 ⁻⁵ mm ³ /N·m	[71]

Table 1. Cont.

One-Step Methods	Substrate			Coating				Ref.
	Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate	
PVD	7075	-	-	Ti, C	-	0.16	5×10^7 mm ³ /N·m	[72]
				Ti, C, N	-	0.13~0.15	$1.43 \times 10^8 \sim 2.11 \times 10^8$ mm ³ /N·m	
		0.156	-	Al, Cr, N	2.566 µm	0.133	-	[73]
	Al-Si	0.34 ± 0.01	4.22×10^{-3} mm ³ /N·m	Cr, Al, N	2.79 µm	0.18 ± 0.02	8.69×10^{-4} mm ³ /N·m	[74]
		-	6.4×10^{-6} ~ 9.8×10^{-6} mm ³ /N·m	Al, Si	~4 µm	0.23~0.35	$0.9 \times 10^{-6} \sim 1.4 \times 10^{-6}$ mm ³ /N·m	[75]
	AlMg1SiCu	-	-	a-C:H, C ₆ H ₅ CH ₃ , C ₂ Cl ₄ /C ₂ Cl ₄	>1 µm	0.042~0.070	-	[76]
	AlSi10Mg	0.6~0.9	10^{-2} mm ³ /N·m	C, O	1.7 µm	0.15~0.41	$1 \times 10^{-6} \sim 1.2 \times 10^{-5}$ mm ³ /N·m	[77]
	3004	-	-	Si-doped DLC	5.5~28.3 µm	-	$6.1 \times 10^{-7} \sim 8.8 \times 10^{-7}$ mm ³ /N·m	[78]
	6061	0.65	-	C	-	0.2~0.25	-	[79]
	AA6061	0.6	-	(Si-CH ₃), Si-(CH ₃) ₃ , (C=C), (C≡C), (C-H)	1.61~2.39 µm	~0.17	-	[80]
Other One-step methods	7075	0.52	5.33×10^{-4} mm ³ /N·m	a-C:H, CH ₄	4 ~28 µm	0.05~0.15	$1.05 \times 10^{-8} \sim 8.51 \times 10^{-8}$ mm ³ /N·m	[81]
	A6061	-	5.66×10^{-4} mm ³ /N·m	Al, Fe, Cr, Co, Ni	420 µm	-	0.29×10^{-4} mm ³ /N·m	[82]
	Resistance seam welding	Al7075	-	WC, SHA	600 µm	-	$0.2 \times 10^{-11} \sim 1.5 \times 10^{-11}$ mm ³ /N·m	[83]
	Spin coating	6061	-	AFD, f-BNNs-ZIF-8@BTA	-	0.64	5.00×10^{-5} mm ³ /N·m	[84]
	Two-component synthesis method	-	6.62×10^{-3} mm ³ /N·m	PU, Al, NiAA	120 µm		$2.00 \times 10^{-3} \sim 5.33 \times 10^{-3}$ mm ³ /N·m	[85]

Note: AO—Anodic Oxidation; MAO—Micro-Arc Oxidation; LSA—Laser Surface Alloying; LC—Laser Cladding; CS—Cold Spraying; PS—Plasma Spraying; SPS—Supersonic Plasma Spraying; EP—Electroless Plating; ED—Electrodeposition; PVD—Physical Vapor Deposition; CVD—Chemical Vapor Deposition; COF—Coefficient of Friction.

2.1. Anodic Oxidation (AO)

In the field of developing wear-resistant coatings for aluminum and its alloys, AO has garnered significant attention as a critical technical approach. AO is an electrochemical treatment process where aluminum and its alloys serve as the anode. When an electric current is applied in a specific electrolyte, aluminum ions migrate toward the anode and react with oxygen ions from the electrolyte to form a dense layer of aluminum oxide film. A robust metallurgical bond with a high binding strength is formed between the oxide film and the substrate. Moreover, the film's primary component, aluminum oxide, possesses excellent hardness and chemical stability, thereby significantly enhancing the wear resistance and corrosion resistance of aluminum alloys [21–24,26]. Additionally, this process is relatively straightforward, cost-effective, and conducive to large-scale industrial production [86,87].

High-pressure hard anodized aluminum oxide coatings was prepared on 6061 aluminum alloy using AO technology and systematically investigated the effects of different anodizing voltages on the structural and mechanical properties of the coatings [26]. The results indicate that the coating prepared at a voltage of 240 V exhibits superior wear resistance and demonstrates a relatively low COF, the narrowest wear width, and the shallowest wear depth under dry friction, water lubrication, and oil lubrication conditions. These characteristics are primarily attributed to the formation of a stable solid lubricating layer under 240 V conditions, as well as the enhanced thickness and hardness of the coating, which improve its load-bearing capacity. Furthermore, the appropriate porosity of the coating facilitates the absorption and dissipation of frictional heat, thereby mitigating adhesive wear. Additionally, the relatively small amount of soft Al_2O_3 particles prevents them from acting as abrasive grains, thus avoiding increasing the COF and wear rate of the AO coating.

Mohammadi et al. fabricated a composite coating on AA1050 aluminum alloy by incorporating Si_3N_4 nanoparticles into the AO electrolyte [21]. The experimental findings indicate that the incorporation of these nanoparticles significantly enhances the hardness of the coating, achieving values in the range of 712–736 HV. As depicted in Figure 1g,h, the COF has decreased from 0.35 for the anodized coating to 0.20, while the wear mass loss has been markedly reduced. Furthermore, the morphology of wear has undergone substantial changes, transitioning from parallel grooves observed on the scratch surface of the bare sample (Figure 1a,b) to an exceptionally smooth wear surface of the composite coating with almost no visible lines (Figure 1e,f). This transformation suggests a shift in the wear mechanism from adhesion–abrasive wear to abrasive wear being predominant. This phenomenon can primarily be attributed to the uniform dispersion of Si_3N_4 nanoparticles within the coating. These nanoparticles fill the pores and become embedded in the coating structure, thereby increasing the surface density and enhancing both the hardness and wear resistance of the coating. Similarly, Remešová et al. demonstrated that the addition of Al_2O_3 and PTFE particles to the electrolyte effectively improves the wear resistance of the AA1050 aluminum alloy surface [22]. This improvement is due to Al_2O_3 enhancing the hardness of the coating and PTFE refining the pore size.

Rawian et al. conducted a comprehensive study on the anodized aluminum composite coating applied to the surface of AA2017-T4 aluminum alloy [23], with particular emphasis on the effects of incorporating heat-treated diamond-like carbon (DLC) on the wear resistance and friction properties of the coating. As illustrated in Figure 2, the porosity and micro-crack density of the DLC-containing coating (A) were significantly reduced, while the surface hardness increased by approximately 10%. In dry sliding friction tests, the COF of the heat-treated DLC coating (B) was notably lower than that of the untreated DLC. Specifically, the DLC coating heat-treated at 500 °C exhibited the lowest COF and a reduced wear rate. This improvement can be attributed to structural changes induced by heat treatment, which enhances the sp^2 graphite phase content and forms a lubricating layer. During the friction process, this lubricating layer effectively reduces the COF. Additionally, the incorporation of DLC refines the coating's pore structure, decreases surface roughness, increases surface hardness, and ultimately enhances the overall wear resistance of the coating.

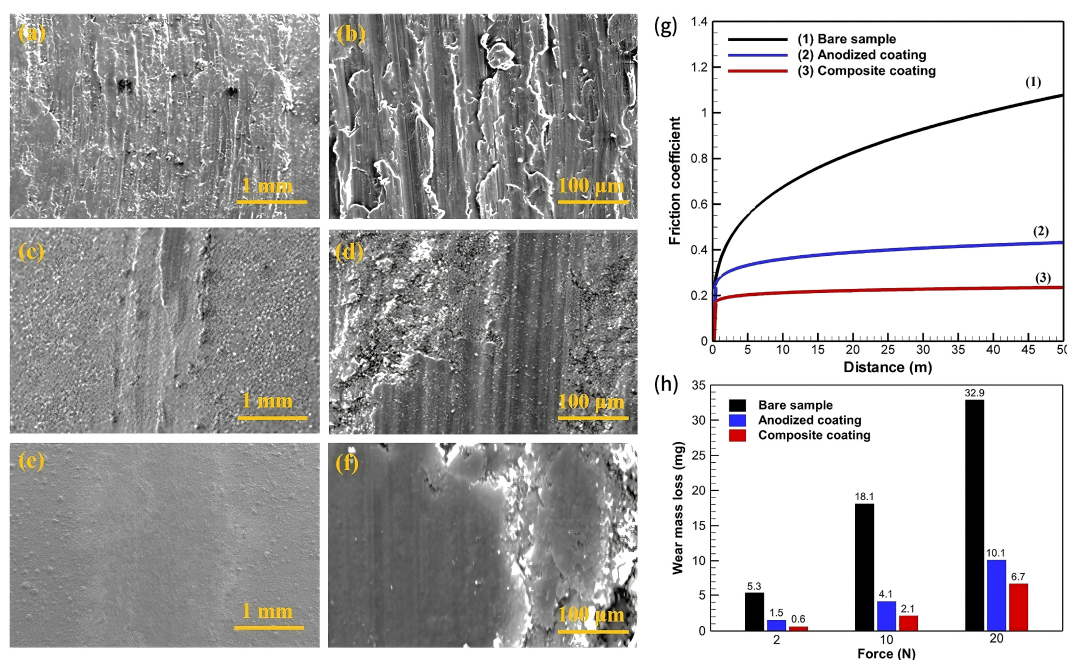


Figure 1. SEM images display worn surfaces of the bare sample (a), anodized coating (c), and composite coating with 6 g/L nanoparticles in the electrolyte (e). Enlarged micrographs of selected regions in (a), (c), and (e) are shown in (b), (d), and (f) respectively. (g) The COF curves of these samples under a 2 N load, at room temperature, with a 250 rpm rotating speed for 50 m. (h) The wear mass loss of the bare sample, anodized layer, and composite coating at different loads (room temperature, 250 rpm, 50 m) [21].

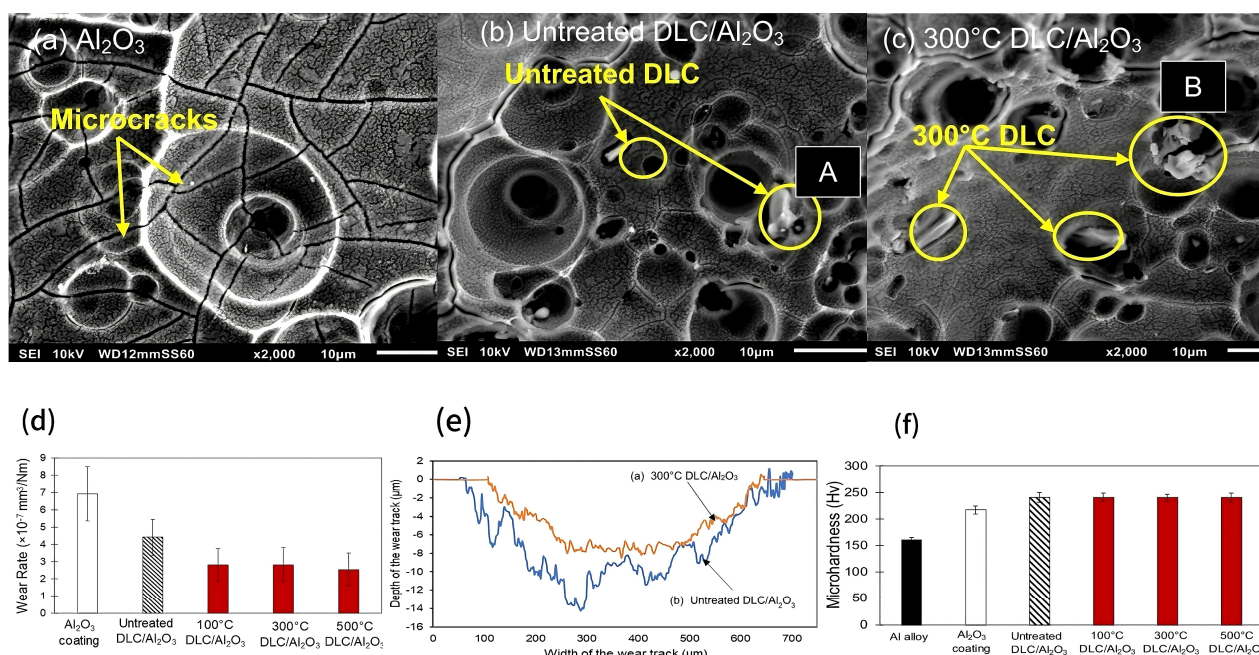


Figure 2. SEM images of composite Al_2O_3 coating: (a) 0 g/L, (b) 1 g/L untreated DLC, and (c) 1 g/L 300 °C DLC. (d) The wear rate of the composite Al_2O_3 coatings. (e) The depth and width of the wear track. (f) Microhardness of Al alloy and composite Al_2O_3 coatings [23].

Ceramic films were fabricated on AA5052 aluminum alloy samples by using the AO technique in sulfuric acid and phosphoric acid electrolytes, respectively [24]. The study investigated the wear resistance and friction properties of the resulting coatings. The results indicate that the usage of both electrolytes effectively reduces the COF of the AO coatings, albeit with differing trends. For the sulfuric acid electrolyte coating, the

COF steadily increases with the number of sliding cycles, whereas the phosphoric acid electrolyte coating exhibits a stepwise change. Additionally, as the AO time increases, the wear rates of the coatings from both electrolytes decrease. Specifically, within the range of 10–20 min, the wear rate of the sulfuric acid electrolyte coating remains relatively stable but decreases further at 30 min. This phenomenon can be attributed to abrasive particles enhancing lubrication between the coating and the friction pair, thereby reducing the COF and improving wear resistance. Moreover, the increased coating thickness enhances its load-bearing capacity, reducing susceptibility to wear under identical friction conditions. Conversely, for the phosphoric acid electrolyte coating, the wear rate continuously decreases within the first 20 min but unexpectedly increases at 30 min. This is likely due to increased pore connectivity or reduced pore wall strength when the AO process treatment time reaches 30 min.

2.2. Micro-Arc Oxidation (MAO)

With the advancement of society and the steadily rising demand, the electrolytes commonly employed in the AO process (e.g., sulfuric acid and chromic acid) are typically highly corrosive, leading to the generation of substantial wastewater during production. If not managed appropriately, this can result in severe environmental pollution. Moreover, traditional anodizing methods generally exhibit disadvantages such as low current density and prolonged processing time [23,88–91]. From the standpoint of enhancing the wear resistance of aluminum alloys, the hardness and thickness of the oxide film formed may occasionally fail to satisfy the requirements of specific high-wear-resistant conditions. In light of these challenges, MAO technology has emerged. MAO represents a novel surface treatment technique that builds upon the principles of AO.

As depicted in Figure 3 [92], the principle can be summarized as follows: During the MAO process, an aluminum alloy (e.g., aluminum) is positioned as the anode within a composite electrolyte solution. Upon connecting the power supply, an initial oxide film forms on the material. As the applied voltage increases to its critical threshold, the weak points of the oxide layer undergo electrical breakdown, initiating micro-arc discharge. The resultant sudden rise in temperature leads to the melting of both the metal and its oxides. Simultaneously, metal atoms react with oxygen atoms from the electrolyte, while other components of the electrolyte also participate in the reaction, thereby promoting the continuous thickening and growth of the oxide film. Following the cessation of micro-arc discharge, the film solidifies within the cooled electrolyte, ultimately forming a ceramic coating with excellent wear resistance and corrosion resistance on the aluminum alloy. Compared to traditional anodizing techniques, this method exhibits a higher growth rate, superior wear resistance, and enhanced hardness [25,88,91]. This suggests that the MAO technology is capable of not only effectively addressing some of the issues inherent in AO but also demonstrating distinct advantages in enhancing the growth rate of the coating and improving wear resistance. Consequently, this technology has garnered significant attention and investigation from scholars and researchers in the field of aluminum alloy surface coating preparation [25,27–46,88,93–104]. Process parameters are critical factors in the MAO process and significantly influence the performance of the generated coating.

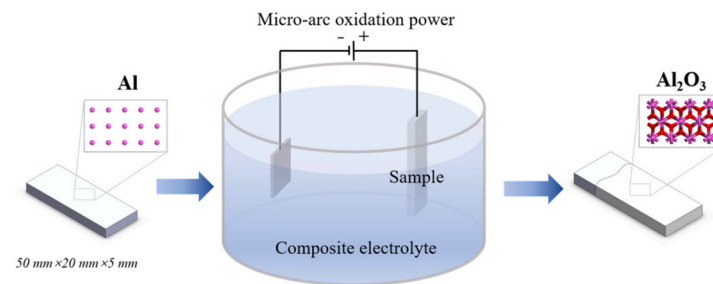


Figure 3. The MAO process for the aluminum alloy [92].

Wang et al. proposed a method for preparing wear-resistant ceramic coatings by dynamically controlling the distance between the anode and cathode using a robotic arm [29]. Research indicates that, when the anode–cathode distance is set to 1 cm, the coating exhibits the lowest average COF and optimal wear resistance. At this point, the porosity of the coating surface decreases. As the anode–cathode distance increases, the equivalent resistance rises and the electric field intensity diminishes, leading to a thinner coating and reduced wear resistance.

MAO coatings were fabricated on 2A50 aluminum alloy by modulating the cathode voltage and systematically investigated their properties [35]. The results indicate that, when the cathode voltage is set to -100 V, the microhardness of the coating reaches its peak value, the wear rate is minimized, and the COF ranges between 0.35 and 0.55. The wear mechanism is primarily characterized by a combination of adhesive wear and abrasive wear. The cathode voltage plays a critical role in determining the microstructure of the coating. The coating prepared at a cathode voltage of -100 V exhibits enhanced density with fewer pores and micro-cracks, which contributes to increased hardness and superior wear resistance during the friction process. Excessively high or low cathode voltage can potentially result in the degradation of the coating structure and a reduction in hardness, consequently impacting wear resistance. Appropriately increasing the current frequency can significantly enhance the wear resistance of the coating [40].

Numerous studies have demonstrated that, during the MAO process, the aluminum component in the aluminum alloy substrate reacts with the oxygen component in the electrolyte, leading to the formation of a significant amount of aluminum oxide phases within the coating [27,101]. Yang et al. demonstrated that the wear rate of the MAO coating on 7075 aluminum alloy is only 1/11th of that of the 7075 aluminum alloy substrate at 300 °C [42]. With the rise in temperature, the increase in the coefficient of friction (COF) and wear rate of the MAO coating, relative to the substrate, remains relatively modest. This phenomenon can primarily be attributed to the presence of the $\gamma\text{-Al}_2\text{O}_3$ and $\alpha\text{-Al}_2\text{O}_3$ phases in the MAO coating, which contribute to enhancing its wear resistance under high-temperature conditions.

Cheng et al. and Zhang et al. both investigated the influence of the NaAlO_2 electrolyte concentration on the wear resistance of the MAO coatings fabricated on aluminum alloys [43,94]. Their findings consistently demonstrate that MAO coatings significantly enhance the wear resistance of the substrate, exhibiting an effective protective function. Additionally, both studies revealed that, as the NaAlO_2 concentration increases, the coating thickness progressively rises, while surface roughness initially decreases and subsequently increases. Furthermore, the bonding strength and wear resistance both exhibit a trend of first increasing and then decreasing with the rising NaAlO_2 concentration. The improvement in the wear resistance of the coating can be attributed to two primary factors. First, the increased content of the $\alpha\text{-Al}_2\text{O}_3$ and $\gamma\text{-Al}_2\text{O}_3$ phases contributes to enhanced hardness and anti-deformation properties of the coating. Second, during the friction process, a portion of the coating detaches and forms abrasive particles, which fill the interstitial spaces between

the coatings. Nevertheless, when the electrolyte concentration exceeds the optimal level, it results in elevated porosity of the coating, thereby diminishing its wear resistance.

Similarly, Sobolev et al. demonstrated that MAO coatings fabricated on aluminum alloy in aqueous solutions and molten salt electrolytes primarily consist of α -Al₂O₃ and γ -Al₂O₃ phases, without additional compounds or through-pores, exhibiting higher hardness and superior wear resistance [102]. This further underscores the critical role of alumina phase composition in enhancing wear resistance. When MAO treatment is conducted in electrolyte systems predominantly containing silicates, the resulting coatings are mainly composed of alumina phases with minor impurity phases such as silicates. These impurities can have a detrimental impact on the performance of the coating. For example, incorporating an appropriate amount of silicate can enhance the density of the coating, which, in turn, improves its wear resistance and other properties [46].

To further enhance the performance of the MAO coatings, researchers incorporated various additives into the electrolyte. These additives actively participated in the MAO process, altered the composition of the coating, and significantly improved its wear resistance. Zhang et al. incorporated MoS₂ nanoparticles to fabricate Al₂O₃/MoS₂ nanocomposite coatings on 2A50 aluminum alloy [34], thereby significantly enhancing the wear resistance of the coatings. As depicted in Figure 4a,b, when the MoS₂ concentration was 4 g/L, the coating demonstrated optimal performance, with an average COF as low as 0.1 and a wear rate of approximately $5.28 \times 10^{-4} \text{ cm}^3/\text{N}\cdot\text{m}$. This improvement can be attributed to the MoS₂ particles filling the micropore defects within the coating and providing a lubricating effect. With varying concentrations of MoS₂, the wear mechanism of the coating also undergoes changes. In the absence of MoS₂, as indicated by the red circle in Figure 4c, deep grooves and fracture characteristics are observed, primarily resulting from abrasive wear, adhesive wear, and oxidative wear. At a concentration of 4 g/L, as highlighted by the red dotted line in Figure 4d, the wear trajectory becomes relatively smooth without noticeable grooves. Under these conditions, the largest surface lubricating film is formed, and the wear mechanism is predominantly boundary lubrication wear. At concentrations of 6 g/L and 8 g/L, due to the presence of pronounced grooves on the lubricating film, adhesive wear and abrasive wear coexist.

MAO coatings were prepared on A356 aluminum alloy by incorporating varying concentrations of NaOH into a 32 g/L NaAlO₂ electrolyte solution [44]. The findings indicate that the addition of NaOH improves the stability of the electrolyte. Specifically, the optimal effect is achieved when 5 g/L NaOH is added, which stabilizes the electrolyte for approximately 35 days. At this concentration, the resulting coating exhibits a dense structure with an exceptionally low wear rate of $4.1 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$ and the smallest depth and width of the wear scar. Nevertheless, excessively high concentrations of NaOH increase the corrosiveness of the electrolyte, thereby negatively impacting the MAO process.

Gao et al. and Xi et al. successfully fabricated MAO coatings doped with distinct substances on 2024 aluminum alloy to enhance its wear resistance [30,31]. Gao's study incorporated hexagonal h-BN nanoparticles, whereas Xi's work utilized quasi-two-dimensional sericite microplates. When the concentration of h-BN reached 10 g/L, the resulting coating exhibited optimal wear resistance, with a COF reduced to only 67% of that of the undoped coating. Similarly, the coating prepared in a 15 g/L sericite electrolyte demonstrated exceptional performance. The primary mechanism underlying the improved friction properties is attributed to the excellent self-lubricating characteristics of both h-BN and two-dimensional sericite microplates. These materials effectively reduce contact between the mating steel balls and the MAO coating by increasing the specific surface area, thereby lowering the COF and mitigating wear. However, an excessively high concentration of h-BN may induce

agglomeration, compromising the density of the ceramic coating and increasing defect formation, which ultimately leads to an elevated COF and diminished wear resistance.

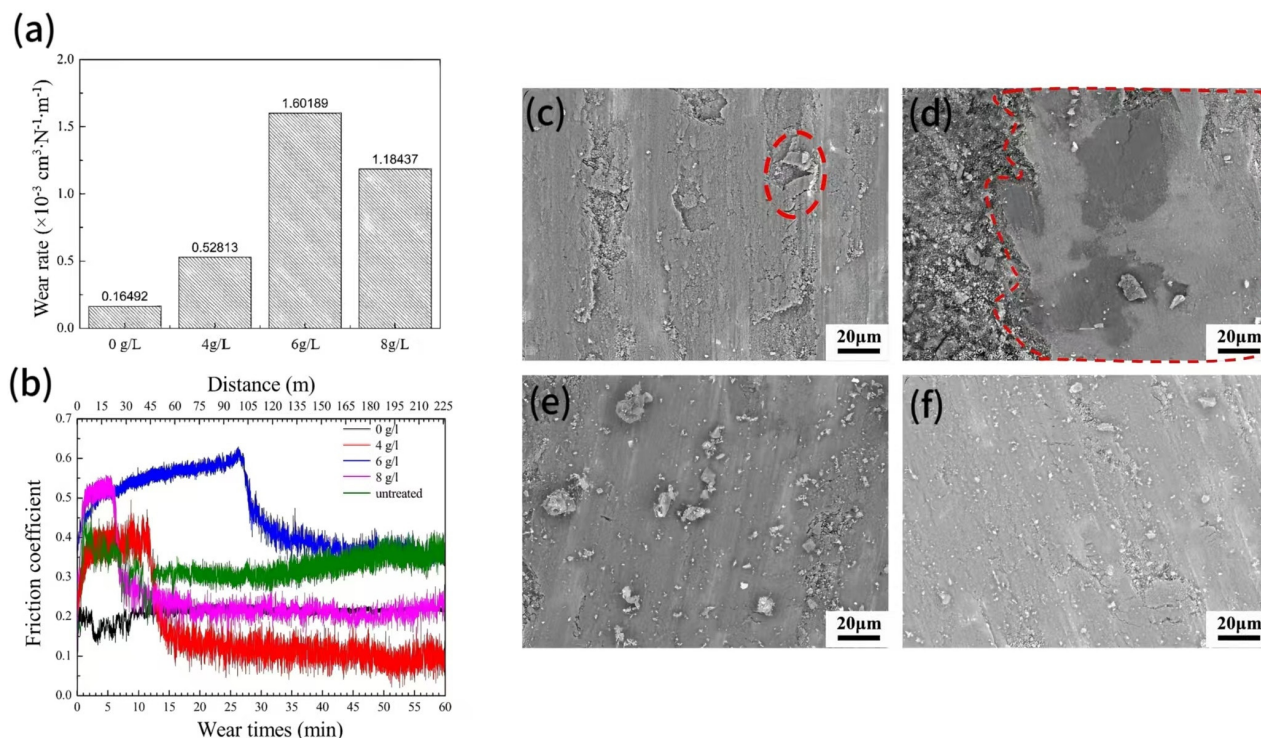


Figure 4. COF curves (a) of MAO coatings under different MoS₂ concentrations. The wear rates (b) of the MAO coatings obtained under different MoS₂ concentrations. SEM of the MAO coatings with different MoS₂ concentrations of (c) 0 g/L, (d) 4 g/L, (e) 6 g/L, and (f) 8 g/L [34].

MAO/TiO₂/PTFE composite coatings were fabricated on 6063 aluminum alloy, thereby significantly enhancing the wear resistance of the coatings [39]. Through electrophoresis deposition, TiO₂ and PTFE particles effectively filled the micropores and cracks in the coating, leading to a reduction in the COF and an improvement in wear resistance. Notably, the COF of the MAO/TiO₂/PTFE coating was reduced to 0.28, while the wear rate reached its lowest value at $(0.92 \pm 0.23) \times 10^{-7} \text{ mm}^3/\text{N} \cdot \text{m}$. The primary wear mechanism of this coating is abrasive wear. The low shear strength structure of the TiO₂/PTFE composite layer allows it to function as an efficient solid lubricant during the sliding process, resisting continuous wear. Additionally, TiO₂ particles contribute to increasing the hardness of the coating, thereby enhancing its wear resistance. Meanwhile, the self-lubricating property of PTFE particles reduces mechanical friction between the coating and the mating material. The synergistic effect of these two components markedly improves the overall wear resistance of the coating.

Truong et al. and Liu et al. prepared MAO coatings on D16T aluminum alloy using various electrolytes and investigated their wear resistance [45,97]. The findings indicated that the wear resistance of all coatings treated by MAO was significantly enhanced. Notably, the MAO coating incorporating graphene exhibits a lower COF and reduced wear rate, thereby demonstrating superior wear resistance. This improvement is primarily attributed to the “rolling effect” of graphene, which provides a lubricating mechanism and effectively reduces the COF. Regarding the wear mechanism, as illustrated in Figure 5 [97], coatings without graphene (A1 and S1) exhibit more micro-cracks and pores. These structural defects are prone to cracking and delamination during the wear process, exacerbating wear damage. In contrast, coatings containing graphene (A2 and S2) form a protective barrier layer under the load due to the deformation and transfer of graphene. This barrier minimizes

direct contact between the counterpart and the coating, thus reducing wear. Additionally, compared to the coating formed in aluminate-based electrolytes, the S2 coating generated in silicate-based electrolytes with added graphene demonstrates a denser structure and fewer pores. The embedding mode allows smaller-sized graphene particles to effectively fill micro-cracks and pores, further enhancing wear resistance [97]. Furthermore, incorporating cobalt hydroxide into silicate-based electrolytes also improves wear resistance. During the MAO process, cobalt hydroxide reacts to form compounds such as cobalt oxide, which alter the surface morphology of the coating. These changes result in a more compact structure, thereby improving the mechanical properties and wear resistance of the coating [45].

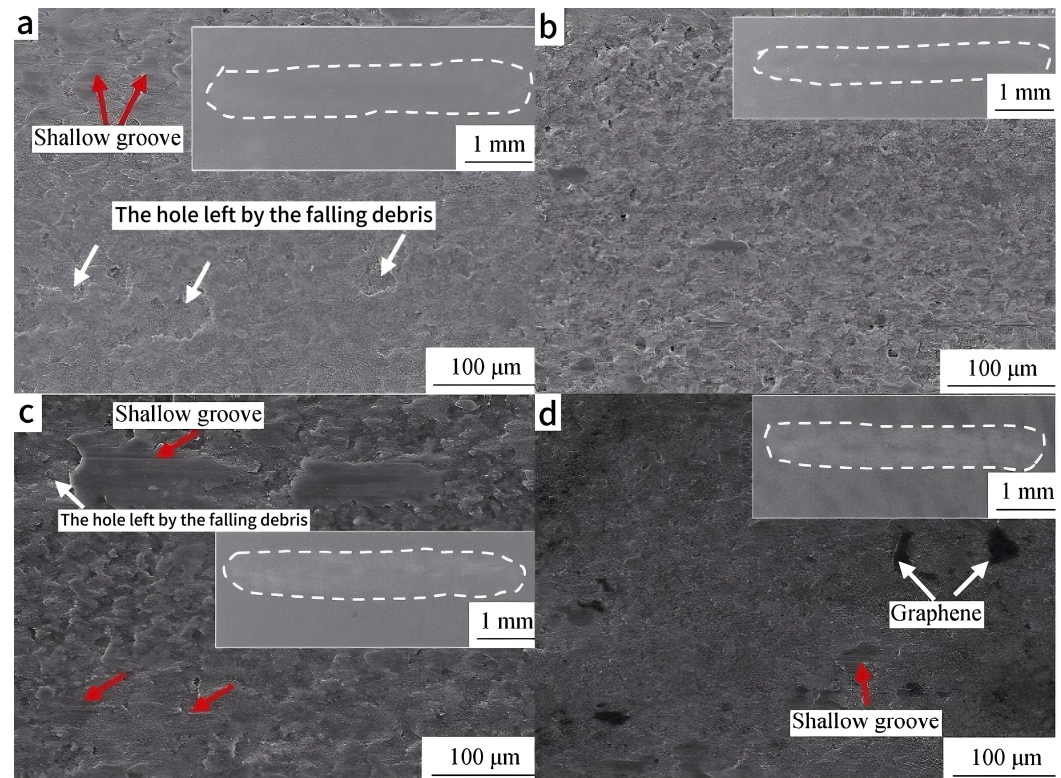


Figure 5. SEM images of wear scars: (a) S1; (b) S2; (c) A1; (d) A2 [97].

In addition, the incorporation of polyethylene glycol (PEG) [28], α - Al_2O_3 particles [41], and graphite [95] into the electrolyte can enhance its ability to resist wear and significantly improve the wear resistance of the coating during friction processes.

2.3. Laser Methods

2.3.1. Laser Surface Alloying (LSA)

LSA technology is progressively emerging as a critical method for enhancing the wear resistance of aluminum alloys. LSA technology involves heating the substrate surface with a laser, thereby melting and diffusing alloy elements or powders into the substrate to form an alloy layer. This process facilitates the uniform distribution of alloy elements, enables precise control over the composition and microstructure of the coating, and allows for tailored enhancement of the surface properties of aluminum alloys [47–49,105]. This clearly highlights the significant potential of LSA technology in the development of high-performance wear-resistant coatings for aluminum alloys.

In the study by Zhang et al., a rare-earth element-modified TiB_2 -reinforced aluminum matrix composite coating was successfully fabricated using the LSA [48]. The research is centered on investigating the impact of varying Scandium (Sc) content levels on the

performance characteristics of the coating. The experimental results indicate that, when the Sc content reaches 0.6 wt.%, the coating demonstrates optimal wear resistance, with a microhardness of up to 920 HV, a COF as low as 0.4, and a wear rate of 24.8 mg/h. In comparison to the coating without the Sc addition, the COF is reduced to two-thirds of its original value, and the wear rate is decreased to four-fifths of its initial level. This outstanding performance can primarily be attributed to the substantial influence of Sc on TiB_2 particles, which effectively refines their size and ensures a more uniform distribution. As depicted in Figure 6, the coating surface with a Sc content of 0.6 wt.% exhibits a smooth morphology, free from significant irregular debris and deep grooves. In this scenario, the predominant wear mechanism transitions from adhesive wear to abrasive wear, thereby further enhancing the wear resistance.

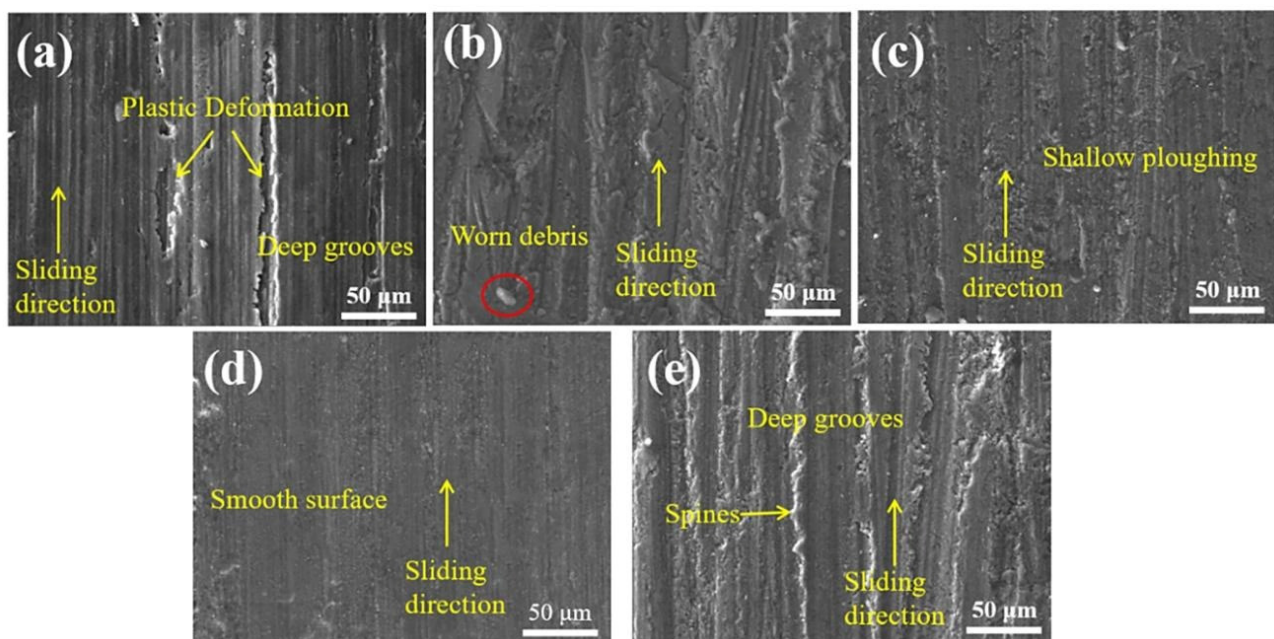


Figure 6. SEM images of a worn surface with different Sc contents: (a) 0 wt.%, (b) 0.2 wt.%, (c) 0.4 wt.%, (d) 0.6 wt.%, and (e) 0.8 wt.% [48].

Chi et al. prepared in situ TiB_2 - TiC -reinforced Fe-Al composite coatings on 6061 aluminum alloy via the LSA [49], utilizing Fe-based self-fusing alloys, B_4C , and Ti mixed powders as raw materials. The research results indicate that, when the Ti content in the coating is 30 wt.% (Sample 1), the average microhardness can reach 520 $\text{HV}_{0.2}$, which is more than seven times greater than that of the substrate. Additionally, the COF is reduced to 0.25 and the wear volume loss is decreased by 92.8% compared to the substrate. When the Ti content in the coating increased to 45 wt.% (Sample 2), the wear volume loss was still reduced by 89.3% compared to that of the substrate. However, the microhardness decreased to 378 $\text{HV}_{0.2}$, and the COF increased to 0.32. In terms of the wear mechanism, as illustrated in Figure 7, the surface of Sample 1 after wear exhibits greater smoothness in comparison to the other components. This can primarily be attributed to the diffusion strengthening effect resulting from the uniform distribution of hard ceramic particles, such as TiB_2 and TiC . Meanwhile, the Fe-Al intermetallic compound contributes to solid solution strengthening, thereby enhancing the coating's resistance to scratching and plastic deformation. This effectively mitigates the occurrence of abrasive wear. In contrast, the coating with a Ti content of 45 wt.% exhibits inferior wear resistance. This is attributed to the excessive presence of ceramic particles, which increases the surface roughness of the

coating. Consequently, this leads to the formation of more cracks and flaky debris within the coating, thereby reducing its wear performance.

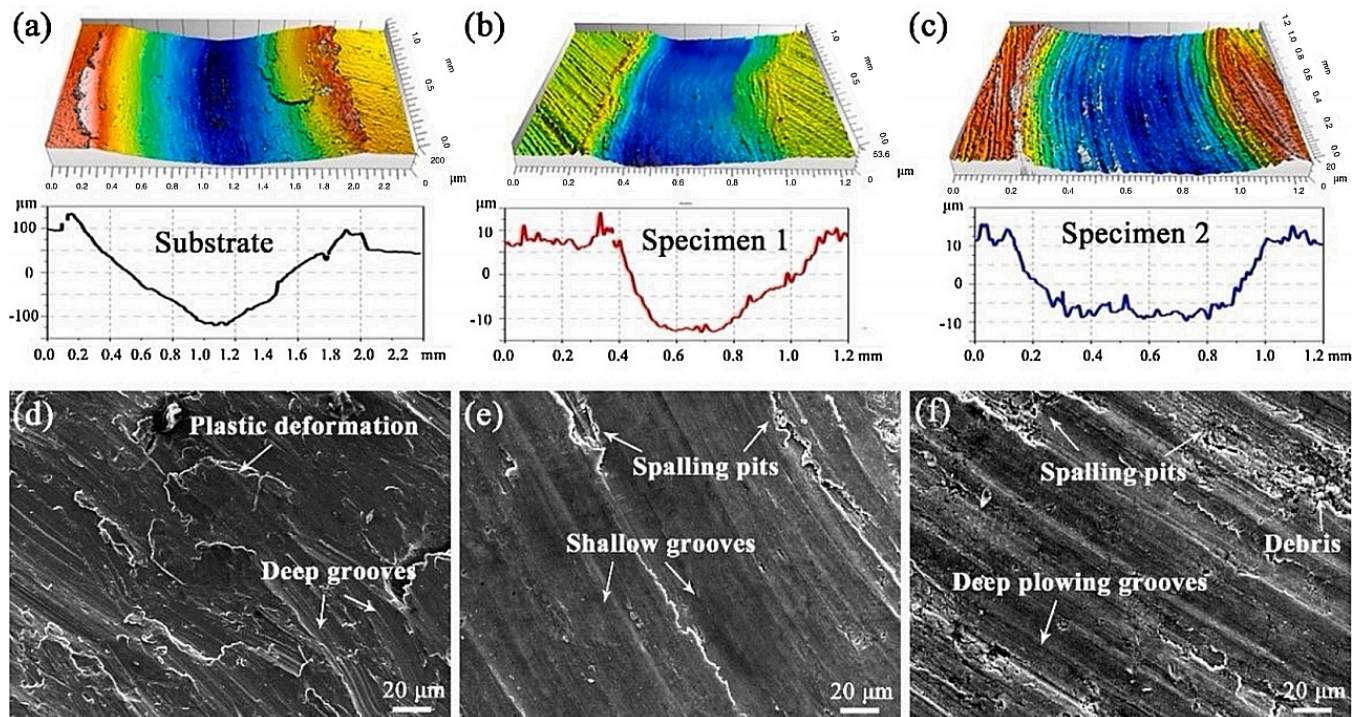


Figure 7. Three-dimensional microscope images, cross-section profile (a–c), and SEM morphologies (d–f) of the worn surface of the 6061 Al substrate (a,d) and the alloyed coatings in Specimen 1 (b,e) and Specimen 2 (c,f) [49].

2.3.2. Laser Cladding (LC)

LC technology offers significant advantages in the field of material surface treatment, allowing for precise control over the melting extent of the substrate while minimizing its impact on the compositional integrity of the cladding layer. This technology emphasizes the independence and integrity of added materials, facilitating the preparation of high-density coatings, accurate control over coating thickness, and demonstrating robust material repair capabilities [105]. As illustrated in Figure 8, this process involves applying cladding materials to the substrate's surface while simultaneously irradiating it with a high-power laser beam at a constant power alongside a hot powder flow. During this operation, some portion of the incident light is reflected, while another portion is absorbed. When the absorbed energy instantaneously exceeds a critical threshold, a thin interlayer between the cladding material and substrate surface rapidly melts, resulting in the formation of a metallic molten pool. Subsequently, this molten pool undergoes rapid solidification to create an additive cladding layer that is metallurgically bonded to the workpiece's substrate surface. LC technology not only significantly enhances wear resistance but also improves surface hardness, corrosion resistance, and other properties [50,51,106]. Due to these remarkable characteristics, LC technology has found extensive applications across various fields, including optics, architecture, automotive engineering, and healthcare.

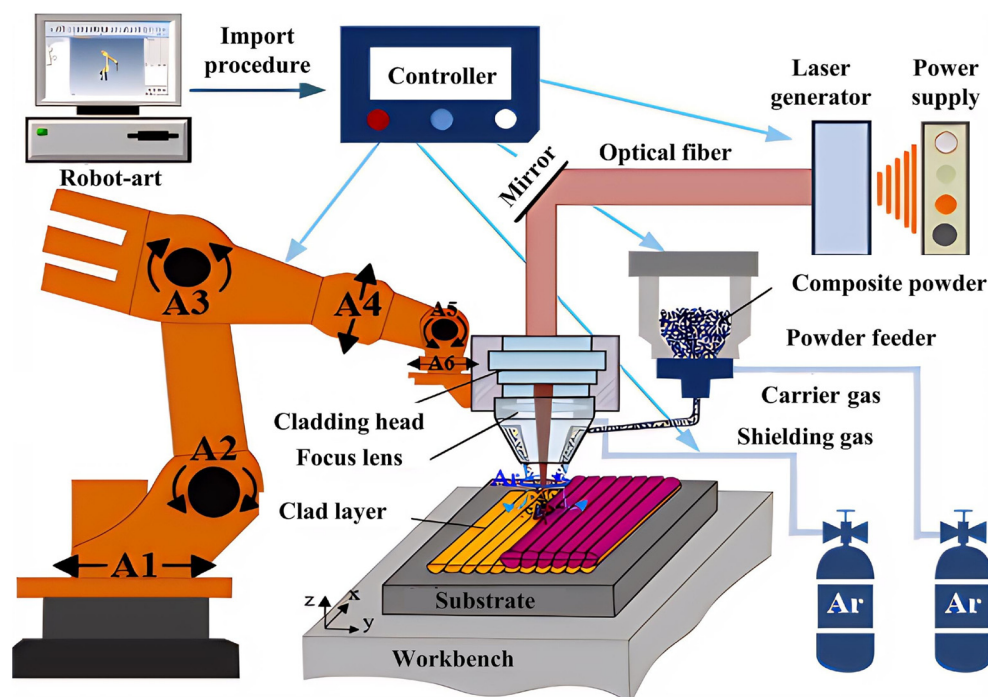


Figure 8. Schematic diagram of the LC system [105].

Li et al. fabricated $\text{Al}_x\text{CrFeCoNiCu}$ high-entropy alloy coatings with varying aluminum contents on 5083 aluminum alloy using LC technology and investigated their wear resistance properties [50]. As the aluminum content increased, the phase structure of the coating underwent significant transformations, transitioning from the FCC1 phase to the FCC1 + BCC1 phase and ultimately forming the BCC1 + BCC2 + FCC2 phase. Intergranular cracks were observed when the value of x reached 2.0. The wear resistance test results demonstrated that the wear rate of the coating was lower than that of the base material. With increasing the aluminum content, the wear behavior exhibited a trend of first decreasing and then increasing. When x equaled 1.5, the coating achieved the lowest wear rate of $6.6 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$. Additionally, the wear mechanism evolved from the severe adhesive wear and delamination fracture characteristic of the base material to predominantly abrasive wear with minor adhesive wear.

Ti/TiBCN coatings were prepared on 7075 aluminum alloy via LC technology and investigated the wear resistance of the coatings under varying TiBCN contents [51]. The results indicate that the incorporation of TiBCN significantly reduces the average COF of the coating, achieving a value of 0.182 at a TiBCN content of 15 wt.%. Under identical wear conditions, the mass loss of the coating is considerably lower than that of the base material. Specifically, the mass loss at 15 wt.% TiBCN content is merely 2.4 mg. In contrast, the base material experienced severe wear, characterized by deep and wide grooves on its surface, whereas the coating displayed narrow, shallow grooves with minimal wear. This behavior can be attributed to the dispersion strengthening effect induced by TiBCN particles, as well as the formation of fine microstructures within the coating during the rapid heating and cooling cycles of the LC process.

Wang et al. successfully fabricated in situ strengthened gradient composite coatings based on Al-Cu on an AlSi10Mg alloy substrate via LC technology [106]. The wear resistance of the coating under various loading and temperature conditions was systematically investigated and analyzed. The results indicate that the average hardness at the bottom of the coating is 320 HV, while, in the central region, it is 256 HV, both significantly exceeding the substrate's hardness of 85 HV. Regarding wear performance, the study revealed that

the coating exhibits lower wear mass loss and COFs compared to the substrate. Under room temperature conditions, as the load increases, the wear mechanism of the substrate transitions from abrasive wear to adhesive wear, whereas the coating predominantly demonstrates abrasive wear characteristics, with some adhesive wear observed under high loads. In high-temperature environments, the wear rates of both the coating and the substrate increase with the rising temperatures. However, at 400 °C, the intermetallic compounds such as Al_2Cu and Al_4Cu_9 present at the bottom of the coating continue to provide effective support, thereby preserving a certain level of wear resistance. At this temperature, the primary friction mechanisms are adhesive wear and plastic deformation.

LC of aluminum alloy surfaces often employs systems such as metal matrix alloys and ceramic composites. Among them, Al_2O_3 ceramics, as reinforcing phases, can enhance the wear resistance of the coating by combining with metal matrices [107]. T.M. Yue et al. prepared Al_2O_3 ceramic coatings on the surface of AA7075 aluminum alloy using CuO and Al powder as raw materials by LC combined with thermal reaction technology [108]. The research found that parameters such as the molar ratio of the powder (such as $2\text{Al}:4\text{CuO}$ and $2\text{Al}:3\text{CuO} + 3\text{SiO}_2$) and the cooling rate would affect the phase composition of $\alpha\text{-Al}_2\text{O}_3$ and $\gamma\text{-Al}_2\text{O}_3$ in the coating. The experimental results show that the addition of SiO_2 can reduce the cooling rate and increase the content of the $\gamma\text{-Al}_2\text{O}_3$ phase, making the microhardness of the coating reach more than 1400 HV, reducing the wear rate by 60% compared with the substrate, and stabilizing the friction coefficient at 0.25–0.30. From the perspective of the friction mechanism, the $\gamma\text{-Al}_2\text{O}_3$ phase formed by the rapid cooling of the laser enhances the metallurgical bonding between the coating and the substrate by reducing the interfacial energy, while the anti-wear skeleton composed of hard Al_2O_3 dots can inhibit abrasive wear. This conclusion is consistent with that of ceramic reinforcement, where hard particles strengthen to improve wear resistance [107,108].

2.4. Spraying Methods

2.4.1. Cold Spraying (CS)

To account for the characteristics of temperature-sensitive materials, CS, as an emerging coating preparation technology, has demonstrated distinct advantages and significant potential in the development of wear-resistant coatings for aluminum alloys. CS is capable of producing coatings characterized by low porosity and high bonding strength. Moreover, the residual stress generated within the coating is compressive in nature, which contributes to enhancing both the wear resistance and service life of the coating. Compared to traditional thermal spraying, CS features a deposition temperature significantly lower than the melting point of the powder material. This effectively prevents the oxidation and evaporation of elements within the coating, thereby preserving the original properties of the material. As such, it is particularly well suited for heat-sensitive metal powders or matrices [52–54,109–111]. CS technology employs high-pressure gas to accelerate powder particles to supersonic velocities, resulting in their high-speed impact on the substrate surface. In the solid state, these particles undergo plastic deformation and subsequently bond with the substrate, resulting in the formation of a uniform and dense coating. Owing to its distinctive characteristics, this method has garnered significant attention from numerous scholars and offers a novel approach for the development of wear-resistant coatings on aluminum alloys.

Five distinct cold-sprayed coatings were prepared on 6061 alloy with nitrogen as the process gas [53] and by varying the temperature and pressure parameters of the gas. As depicted in Figure 9, the T7.5P4.5 coating (with a gas temperature of 750 °C and gas pressure of 4.5 MPa) exhibited superior performance. Its wear rate was measured at $5.10 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$, with a relatively stable COF averaging 0.30 ± 0.06 and fluctuating

between 0.3 and 0.7. The wear depth was approximately $38.736 \mu\text{m}$, and its wear marks were relatively shallow. Conversely, the T6P4.2 coating (with a gas temperature of 600°C and gas pressure of 4.2 MPa) demonstrated inferior performance, with a wear rate reaching $6.34 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. Additionally, the COF exhibited significant fluctuations, and the wear depth was approximately $46.49 \mu\text{m}$. From the analysis of the wear mechanism, each coating displayed a range of distinct wear modes. Due to its high porosity and low hardness, the T6P4.2 coating predominantly exhibited delamination wear characteristics. As shown in Figure 9a,a₂, micro-cracks, extensive spalling, and a relatively high surface roughness were evident in its wear marks. For coatings with higher hardness, such as T7.5P4.5 and T7.5P4.8 (with a gas temperature of 750°C and gas pressure of 4.8 MPa), abrasive wear was the predominant feature. As illustrated in Figure 9d,d₁,e,e₁, the wear marks on these coatings appeared thinner and were accompanied by plastic deformation.

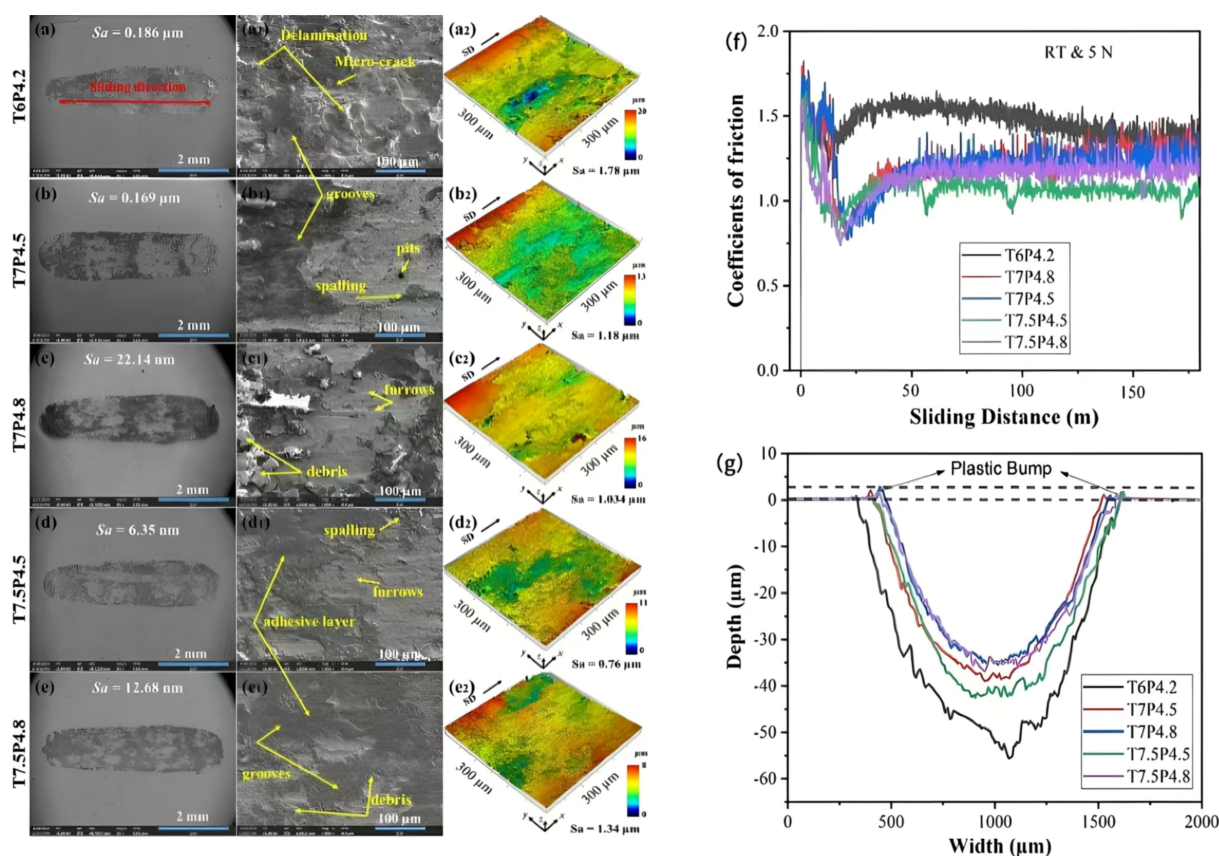


Figure 9. SEM images of the wear track morphology and areal surface roughness (Sa) after wear tests under a normal load of 5 N and at room temperature: (a–a₂) T6P4.2, (b–b₂) T 4.5, (c–c₂) T7P4.8, (d–d₂) T7.5P4.5, and (e–e₂) T7.5P4.8. The Sa value mentioned with white (a,b,d,e) is the polished surface roughness value of the specimens. Evaluation of the sliding friction of the cold-sprayed specimens at a load of 5 N and a sliding frequency of 30 Hz, (f) COF, and (g) wear depth [53].

Jafari et al. and Wang et al. conducted comprehensive analyses regarding the influence of the reinforcing phase content on the tribological behavior of composite coatings [54,109]. The former primarily focuses on cold-sprayed aluminum-reinforced crystalline composite coatings, while the latter centers on cold-sprayed Ni-Ti₃AlC₂ composite coatings. Studies indicate that the incorporation of quasi-crystalline particles can enhance the wear resistance of cold-sprayed aluminum alloy coatings by approximately sevenfold. Notably, coarse-sized quasi-crystalline particles demonstrate a superior effect in improving wear resistance. With the increase in Ti₃AlC₂ content, the wear rate of the Ni-Ti₃AlC₂ composite coating decreased substantially, from $8.96 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$ for the substrate to

$1.87 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. Meanwhile, as the content of Ti_3AlC_2 increases, both the depth and width of the wear tracks gradually decrease, while the hardness and adhesion strength of the coating also increase correspondingly. Furthermore, the incorporation of the reinforcing phase can alter the friction mechanism of the coating. For instance, the addition of quasi-crystalline particles results in a shift of the friction mechanism from adhesive wear to predominantly abrasive wear. With the increase in the Ti_3AlC_2 content, the friction mechanism changes from adhesive wear to fatigue wear.

2.4.2. Plasma Spraying (PS)/Supersonic Plasma Spraying (SPS)

PS technology, owing to its distinct advantages, has garnered significant attention in the field of aluminum alloy wear-resistant coating preparation. As shown in Figure 10 [61], the fundamental principle of this technology involves the configuration of the spray gun, where the cathode is connected to the negative terminal of the power supply and the anode is linked to the positive terminal. The working gas is ionized through high-frequency spark ignition, and a non-transferred plasma arc is formed under the influence of three distinct compression effects. The powder gas is injected into the arc, where the powder is rapidly heated to achieve a molten or semi-molten state. Then, propelled by a high-speed plasma jet, the material is rapidly deposited onto the pretreated substrate surface. After the particle impact, it flattens, cools, and solidifies and stacks to form an adhesive coating. This technology is capable of not only refining the microstructure of the coating but also significantly enhancing its hardness, wear resistance, and other properties [55,57,58,61,62]. Currently, PS technology has gained extensive application across various domains, including aerospace, automotive, biomedicine, and other fields. The following section provides an overview of the research status regarding the use of PS in the development of wear-resistant coatings on aluminum alloys.



Figure 10. Schematic diagram of plasma spray [61].

AlSi30Cu5 coating was prepared on 6061 aluminum alloy using PS technology [57]. It was observed that the coating primarily consists of $\alpha\text{-Al}$, $\beta\text{-Si}$, and $\theta\text{-Al}_2\text{Cu}$ phases. Notably, the size of $\beta\text{-Si}$ in the coating has been reduced from $3.51 \mu\text{m}$ to $2.06 \mu\text{m}$. The refinement effect can be attributed to the rapid cooling that occurs during the PS process, effectively preventing the coarsening of $\beta\text{-Si}$. The COF of friction is 0.31, which is lower than that of the substrate (0.46). Additionally, the wear rate of the coating is only 20% of that of the substrate. This suggests that the AlSi30Cu5 coating can offer efficient wear protection for 6061 aluminum alloy and substantially enhance its wear resistance.

He et al. employed PS technology to fabricate three distinct coatings on 7005 aluminum alloy: Ni-based alloy coating (referred to as S1), Al_2O_3 -reinforced Ni-based alloy composite coating (referred to as S2), and $\text{Al}_2\text{O}_3\text{-CeO}_2$ -reinforced Ni-based alloy composite coating (referred to as S3) [58]. The results indicate that the three coatings exhibit superior wear resistance compared to the base materials. Under a low load condition ranging from 6 to 9 N, the wear volume of the S3 coating is only 0.7 to 0.9 mg, and the COF remains within the range of 0.1 to 0.32. When the load exceeds 9 N, the wear resistance of the S3

coating remains superior to that of the other control groups. This phenomenon can be attributed to the synergistic strengthening effect between Al_2O_3 and CeO_2 particles. In terms of the wear mechanism, as the load increases, the wear mechanism of the S3 coating transitions from micro-cutting wear to micro-brittle fracture wear and slight oxidation wear. Even so, the S3 coating demonstrates significantly lower wear losses compared to the other coatings under evaluation across this load range. This further suggests that the synergistic interaction between Al_2O_3 and CeO_2 substantially improves the coating's resistance to friction.

Abbas et al. fabricated ZAC ($\text{ZrO}_2/\text{Al}_2\text{O}_3$ composite coating) and FZA (the fused $\text{ZrO}_2/\text{Al}_2\text{O}_3$ coating) coatings on an Al-Si alloy using PS technology [62]. To assess the wear resistance of the two coatings, the research team systematically designed and carried out tribological wear experiments under various loads and sliding speeds. The experimental results demonstrate that, under all tested conditions, the wear resistance of both ZAC and FZA coatings is significantly superior to that of the Al-Si alloy matrix. Especially under 10 N load and 1 m/s sliding speed, the two coatings show the best tribological properties. The FZA coating demonstrates exceptional performance, characterized by a COF of 0.357 and a wear rate of 7.8×10^{-5} g/m. This outstanding performance can primarily be attributed to its high surface hardness and the friction-reducing effect of solid lubrication. During wear, these factors facilitate the formation of a uniform and stable ceramic lubrication layer, which effectively minimizes friction and wear. With the increasing load, both coatings exhibited an upward trend in their COFs and wear rates. In terms of sliding velocity, the COF and wear rate of the Al-Si alloy initially decrease and subsequently increase. In contrast, the COF and wear rate of the ZAC and FZA coatings initially decreased but subsequently exhibited a slight increase due to high-speed sliding, which led to the delamination of the oxide layer. In general, FZA coatings exhibit exceptional wear resistance across a range of working conditions, making them an ideal coating option for enhancing the tribological performance of Al-Si alloys.

Based on PS technology, researchers have advanced to developing SPS technology. In comparison with conventional PS, this innovative technology exhibits a higher spraying velocity, enhanced coating uniformity, and superior adhesion performance. Additionally, it operates at a lower temperature than traditional methods while achieving a notable improvement in overall efficiency.

Dong et al. investigated the wear resistance of an Al-25Si-4Cu-1Mg coating prepared via SPS [56]. The wear results are presented in Figure 11a–d. The 2A12 aluminum alloy predominantly exhibits adhesive wear, characterized by prominent adhesive marks and extensive peeling fragments on its surface. In contrast, the coating primarily undergoes abrasive wear, featuring relatively shallow surface scratches and smaller fragment sizes. As illustrated in Figure 11e,f, compared to the 2A12 aluminum alloy substrate, this coating demonstrates a low and stable COF during the friction and wear test, with minimal fluctuations. The width of its wear scar is approximately one-fourth that of the 2A12 aluminum alloy, and its wear volume is only one-third of the latter. This exceptional wear resistance originates from its high hardness, which effectively mitigates wear during the friction process. Moreover, the uniformly distributed β -Si hard phase can resist scraping and reduce the contact area between the α -Al matrix and the friction balls, thereby minimizing adhesive wear. Even if the β -Si phase fractures and peels off, its fine particles continue to reduce friction and enhance the overall wear resistance. However, after heat treatment, due to grain growth of Al and Si, the hardness decreases, the wear rate increases, and multiple mixed wear mechanisms emerge simultaneously [59]. In summary, high-silicon aluminum alloy coatings possess significant potential for wear resistance; however, heat treatment can alter their microstructure and properties, exerting complex influences on wear resistance.

Consequently, in practical applications, the composition, processing methods, and heat treatment conditions must be comprehensively evaluated to optimize wear resistance.

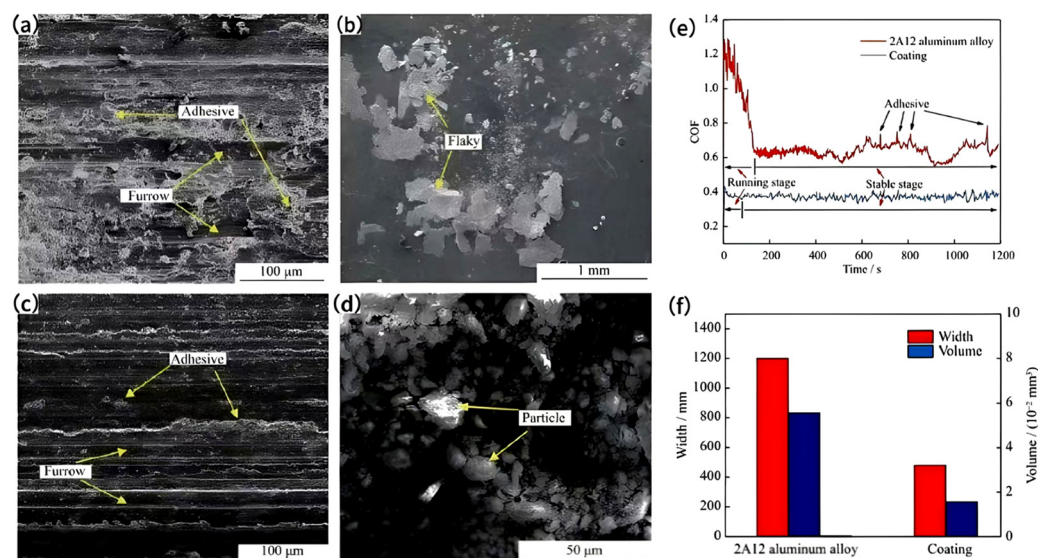


Figure 11. Wear marks and debris morphology of the (a,b) 2A12 aluminum alloy and (c,d) coating. (e) COF of the 2A12 aluminum alloy and coating. (f) Wear width and volume of the 2A12 aluminum alloy and coating [56].

Han et al. investigated the friction and wear properties of ZL109 aluminum alloy by applying SPS of TiO_2 coatings on its surface and optimizing the relevant parameters [60]. Under varying loads (100–140 N) and at a temperature of 120 °C, the COF of the coating ranged from 0.05 to 0.08, increasing with the applied load. The wear mechanism transitioned from abrasive wear to adhesive wear and oxidative wear. This transformation is attributed to the fact that, under low-load conditions, the coating surface primarily experiences mild abrasive particle action. As the load increases, friction-induced heat generation rises, elevating the temperature and causing the rupture of the boundary lubricating film, thereby intensifying the adhesive wear and oxidation reactions. After parameter optimization (current: 439 A, voltage: 129 V, and argon gas flow rate: 117 m^3/h), the porosity of the coating was reduced to 1.06%, the microhardness reached 1041 $\text{HV}_{0.2}$, the COF stabilized at 0.09, and the wear volume per unit area decreased to $2.1 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$. Compared to the unoptimized coating, the optimized coating exhibited significantly enhanced wear resistance, reducing the wear volume by 69.9%. This improvement can be attributed to the denser structure and increased hardness of the optimized coating, which enhances its ability to resist wear.

2.4.3. Other Spraying Methods

UHMWPE/GNPs nanocomposite coatings were fabricated on AA2028 aluminum alloy via electrostatic spraying technology (EST) [112]. The research demonstrated that incorporating graphene nanoplates (GNPs) can significantly decrease the COF and wear rate of the coating. Notably, the UHMWPE/1 wt.% GNP composite coating exhibited the most superior performance, with a 29% reduction in COF and a 36% reduction in wear rate compared to pure UHMWPE. This can be attributed to the layered structure of GNPs, which provides a lubricating effect, as well as their uniform dispersion within the matrix. Further tests were performed on the coating under varying sliding speeds. The results indicated that the COF decreased as the speed increased, with a maximum reduction of 42%. Conversely, the wear rate exhibited an increasing trend with higher sliding speeds. From the perspective of the wear mechanism, at low speeds, the predominant form of

wear is abrasive wear. At high speeds, however, the wear mechanism transitions to plastic deformation wear as a result of polymer softening. In addition, plasma treatment employs oxygen in the fourth state of matter to eliminate impurities and defective layers on the substrate surface via chemical reactions or ablation. This process enhances the surface energy, thereby promoting the adhesion between the coating and the substrate [113].

T-PI-MPS and PDMS-PI composite coatings were prepared on 7050 aluminum alloy via spraying technology [63,64]. Both coatings demonstrated superior wear resistance. Specifically, the wear rate of the T-PI-MPS composite coating was reduced by 85% compared to the PI-MPS coating, with the COF decreasing from 0.75 to 0.58. In comparison, the PDMS-PI composite coating exhibited a significant reduction in wear rate of 38.5% relative to the PI and SiO₂-PI coatings, and the COF dropped from 0.33 to 0.07.

These differences can be attributed to variations in the wear mechanisms and contributing factors. The wear process of the T-PI-MPS coating can be categorized into three stages: Initially, degradation occurs due to the insufficient toughness and wear resistance of the MPS enrichment layer. During the intermediate stage, when friction balls interact with the PI enrichment layer, cracks form and subsequently spall due to stress concentration and defects. In the final stage, Ti₃AlC₂ fills these cracks, effectively inhibiting further wear. This exceptional wear resistance is attributed to the suppression of PI swelling and corrosion by the MPS enrichment layer, the high load-bearing capacity of the PI enrichment layer, and the crack-filling and corrosion path-extending effects of Ti₃AlC₂ [63].

In the PDMS-PI coating, during friction, the first contact involves a dense film generated by the cross-linking esterification reaction. This film reduces surface activity and introduces heat-resistant Si-O groups, thereby enhancing the oxidation resistance and thermal stability of the coating. Subsequently, uncross-linked PDMS is released to provide lubrication for the system and effectively reduce the COF. Ultimately, a friction transfer film is formed, which significantly enhances the overall wear resistance of the coating [64].

2.5. Deposition Methods

2.5.1. Electroless Plating (EP)

EP is a sophisticated technology that deposits metallic or alloy coatings onto the surface of a substrate via self-catalytic reactions, eliminating the need for an external current source. Compared with other coating preparation methods, EP demonstrates advantages such as uniform coatings, the ability to deposit onto complex-shaped substrates, and relatively simple equipment requirements. Consequently, it exhibits broad application potential in the surface treatment of aluminum alloys. Next, by integrating the insights from References [65–67,114–116], we will conduct an in-depth exploration of the specific applications of EP in the preparation of wear-resistant coatings for aluminum alloys, process optimization, and its impact on coating performance.

EnI-P-ZnO nanocomposite coatings were prepared on 6061 aluminum alloy via EP [65]. Their study demonstrated that the incorporation of Aliquat 336 surfactant significantly improved the wear resistance of the coatings. Specifically, prior to a concentration of 1.5 g/L, an increase in the surfactant concentration led to a gradual enhancement in hardness and a corresponding reduction in the wear rate. Regarding the wear mechanism, in the absence of surfactants, the coatings predominantly experienced adhesive wear, which resulted in severe scratches and a relatively high wear rate. Upon the addition of surfactants, the wear mode shifted primarily to abrasive wear, thereby reducing the wear rate. This improvement can be attributed to the increased hardness of the coatings, which enhances their resistance to plastic deformation, as well as the smoother surface texture achieved, which reduces the COF and consequently lowers the wear rate.

Parthiban et al. and Arumugam et al. fabricated electroless nanocoatings on LM6 alloy and carried out comprehensive investigations into their wear behaviors [114,116]. The experimental results consistently demonstrate that the incorporation of surfactants (sodium lauryl sulfate, SLS) and nanomaterials leads to a significant enhancement in the microhardness of the coating, optimization of the microstructure, and an effective reduction in the wear rate. In a previous study [66], similar results were also obtained: After incorporating CeO₂ nanomaterials into the Ni-B alloy composite coating, it was evident that the coating grains were substantially refined, and the microhardness was significantly enhanced concurrently. In terms of wear performance, the composite coating demonstrates superior characteristics. It exhibits a lower wear rate compared to both the pure Ni-B coating and the aluminum alloy substrate, as well as a reduced COF. These advantages are especially pronounced under high-load conditions. This exceptional performance can be attributed to the refined grain structure, the improved interfacial bonding strength, and the strengthening effect induced by CeO₂ particles.

Mohanty et al. successfully prepared Ni-P-MoS₂ composite coatings by incorporating MoS₂ particles into the EP solution [115]. They compared the properties of textured and untextured surfaces of Al6060 aluminum alloy and simultaneously examined the effects of oxalic acid and hydrazine-based plating solutions on coating formation. The experimental results indicate that the COF for the textured coating samples ranges from 0.23 to 0.38, which is substantially lower than that of the untextured samples, which varies between 0.4 and 0.49. Under loads of 8 N and 12 N, micro-scratches were observed on the textured samples, extending to the substrate. In contrast, this phenomenon was not observed in the non-textured samples. In addition, the coating prepared in the oxalic acid plating solution demonstrates superior microhardness and frictional performance. The experiment further demonstrated that MoS₂, as a solid lubricant, plays a crucial role in forming a friction-enhancement layer on the coating surface. However, the Ni-P electroless coating, even without additional components, can enhance wear resistance and achieve a substantial increase in microhardness when subjected to heat treatment [67].

2.5.2. Electrochemical Deposition (ED)

ED technology has emerged as a critical method for enhancing the wear resistance of aluminum alloys, owing to its advantages, including precise control over coating composition and thickness, as well as the capability to deposit coatings onto substrates with complex geometries [69–71,117,118]. In principle, electrochemical deposition involves harnessing the effect of an electric field to induce reduction reactions of metal ions or other particles on aluminum alloys, thereby forming coatings [71,118]. Next, this paper will elaborate on some specific applications of ED technology in the preparation of wear-resistant coatings for aluminum alloys.

Luo et al. synthesized Ni/GO composite coatings on 2024-T6 aluminum alloy via electroplating [70]. The results indicate that the Ni/GO coating exhibits the lowest COF, minimal wear volume, and shallowest wear track. This can be attributed to the unique structure and properties of graphene oxide (GO). As depicted in Figure 12, during the friction process, interlayer sliding friction occurs, and the dislodged particles actively participate in the friction process by filling the pores and thickening the transfer film. Consequently, this mechanism effectively reduces the COF and enhances the wear resistance of the coating.

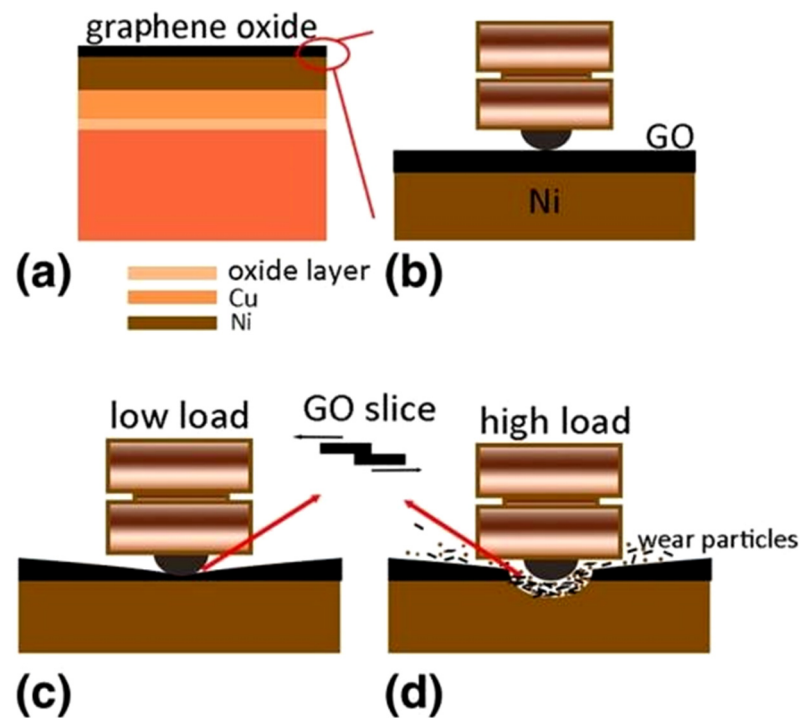


Figure 12. Wear process mechanism diagram. (a) In the case of a multi-layer composite coating, when the applied load is relatively low, the grinding balls come into contact with the surface graphene oxide layer. (b) Slight deformation occurs on the surface of the graphene oxide layer under the influence of mechanical stress. (c) During the friction process, sliding friction occurs between adjacent graphene oxide layers. (d) With a slight increase in the applied load, the surface film and graphene oxide layer are compressed, resulting in the formation of a certain quantity of wear particles [70].

Huang et al. investigated the ED of Ni-SiC composite coatings on A356 aluminum alloy and revealed that the content of SiC particles significantly influenced the hardness and wear rate of the coating [71]. In a dry friction environment, the coating containing 8.0–10.0 vol.% SiC particles exhibited a lower COF and wear rate due to its higher hardness-to-elastic modulus ratio (H/E). Under lubricated friction conditions, the coating with 8.0–10.0 vol.% SiC particles also demonstrated superior performance at a load of 150 N. Notably, the coating with 12.3 vol.% SiC particles achieved even better wear resistance at a load of 200 N due to the formation of oil storage cavities. This phenomenon can be attributed to the uniform dispersion of SiC particles in the nickel matrix, which effectively enhances the diffusion strengthening effect, thereby inhibiting dislocation movement and increasing the hardness of the coating. Additionally, the presence of SiC particles contributes to the stability of the lubricating film, reduces direct contact between friction pairs, and consequently decreases wear.

2.5.3. Physical Vapor Deposition (PVD)

In the research domain of wear-resistant coatings for aluminum alloys, PVD technology has garnered significant attention owing to its distinct advantages. PVD technology encompasses a range of specific methods, including magnetron sputtering, pulsed laser deposition (PLD), and plasmon-based ion implantation and deposition (PBII&D), and plays a critical role in enhancing the surface properties of aluminum alloys [72–77,119].

Among the various PVD methods, magnetron sputtering has been extensively utilized owing to its superior sputtering and deposition rates, higher ionization efficiency, and the capability to sustain discharge at lower operating pressures and voltages [73–75,77,119,120]. As depicted in Figure 13, the primary principle involves the introduction of argon gas as the working medium within the vacuum chamber. Under the influence of a high-voltage electric

field, the argon gas undergoes ionization, generating argon ions and electrons. Positively charged argon ions are accelerated by an electric field and subsequently collide with the target material, resulting in the ejection of target material atoms through a sputtering process. These sputtered atoms migrate towards the substrate and form a film on its surface through deposition. If a reactive gas is introduced, it may chemically interact with the atoms of the target material to form a compound film. Meanwhile, the magnetic field positioned beneath the target material confines the movement of electrons to a spiral trajectory, thereby enhancing both the gas ionization efficiency and the sputtering rate. Radio frequency magnetron sputtering is extensively utilized for the deposition of various metals (including alloys), semiconductors, and insulating materials [120]. Additionally, this technique has significantly contributed to the advancement of aluminum alloy wear-resistant coating technology.

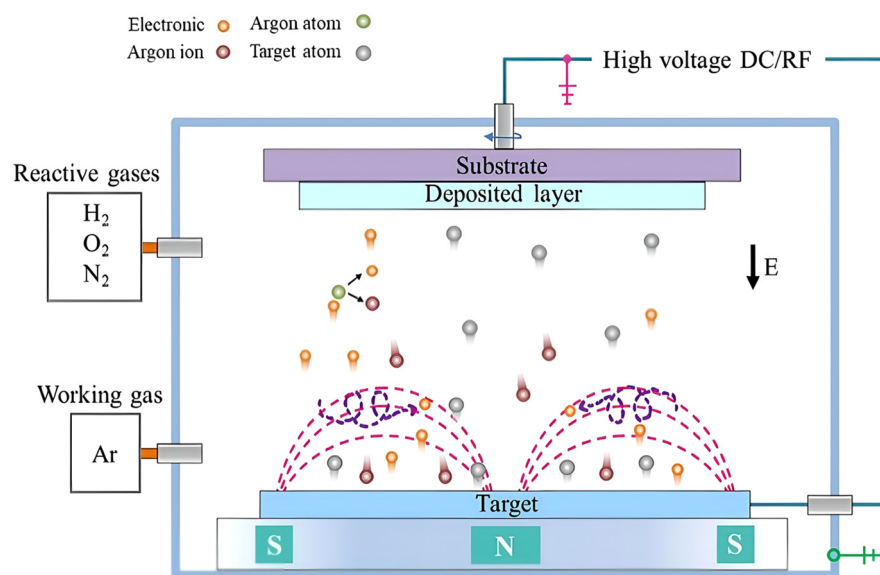


Figure 13. Schematic illustration of the equipment and principle of a typical magnetron sputtering technique [120].

AlCrN coatings were fabricated on Al7075 alloy using magnetron sputtering technology [73], utilizing high-purity aluminum and chromium as sputtering targets. The research findings indicate that the AlCrN coating exhibits a face-centered cubic structure, which substantially enhances the wear resistance of the Al7075 alloy and effectively reduces the COF. Under varying load conditions, the wear rate of the coated samples is significantly lower than that of the uncoated samples, resulting in reduced wear loss. This can be attributed to the fact that chromium and nitride particles in the coating enhance the bonding strength, increase the hardness, and, simultaneously, the reduction in surface roughness leads to a decrease in friction [121].

Mehran et al. investigated the wear resistance of CrAlN multilayer coatings deposited on hypereutectic Al-Si alloys via magnetron sputtering [74]. The research findings indicate that the CrAlN coating exhibits a highly dense microstructure, with its surface roughness decreasing to 14 nm. This represents a substantial improvement compared to the uncoated samples. Additionally, the hardness of the coating is enhanced by approximately 5.8 times. In terms of friction and wear performance, the COF of the coating was reduced to 0.18 ± 0.02 , and the wear rate decreased to $8.69 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$, indicating a substantially lower level of wear. This improvement can be attributed to the incorporation of aluminum into the coating, which enhances its resistance to ploughing wear and delamination failure. In addition, the higher hardness and lower surface roughness significantly

contribute to a more effective reduction in the COF. In addition, the coating exhibits excellent adhesion to the substrate, with a critical load of 2341 mN, thereby ensuring the stability and reliability of the coating during its service life.

Xu et al. investigated the use of magnetron sputtering for depositing Al-Si coatings with varying silicon contents on Al-Si alloys [75] and systematically evaluated their wear resistance properties in high-temperature conditions. The research revealed that the Al-Si coating with 25.2 at.% Si exhibited the most favorable performance, achieving a COF as low as 0.231 at high temperatures and maintaining a wear rate within the relatively low range of $0.9 \times 10^6 \text{ mm}^3/\text{N}\cdot\text{m}$ – $1.4 \times 10^6 \text{ mm}^3/\text{N}\cdot\text{m}$. This can be attributed to the unique microstructure of the coating, which forms a three-dimensional network structure that effectively restricts the movement of Al dislocations and thereby enhances hardness. Meanwhile, the silicon oxide formed through the reaction of Si particles with moisture at high temperatures serves as a lubricant, thereby reducing the COF. Moreover, the coating's high hardness and excellent load-bearing capacity confine wear to the surface contact area, thereby preventing fractures. Consequently, the coating demonstrates significantly enhanced wear resistance, offering an improved surface protection strategy for the application of Al-Si alloys in high-temperature environments.

Kaczmarek et al. investigated the influence of deposition atmosphere pressure and composition on the wear-related properties of 7075 aluminum alloy by fabricating a carbon coating on its surface using PLD [72]. The nitrogen-free Ti/a:C coating demonstrated superior performance, exhibiting an exceptionally low wear rate of $5 \times 10^7 \text{ mm}^3/\text{N}\cdot\text{m}$ and a COF of 0.16. The incorporation of nitrogen into the coating will decrease its critical load and lead to an increased wear rate. This occurs because nitrogen reduces the kinetic energy of the coating particles and weakens the chemical bonding between the coating and the substrate.

PBII&D is additionally utilized in the preparation of coatings. Tokuta et al. fabricated undoped and chlorine-doped a-C:H films on aluminum alloys using PBII&D technology [76], with toluene and tetrachloroethylene serving as precursors. The research demonstrates that chlorine doping effectively decreases the COF. Specifically, when the Cl/(C + Cl) ratio is maintained within the range of 0.013–0.083, both the wear area is significantly reduced and the wear resistance is notably enhanced. Surface analysis confirmed the formation of a hydrated friction film containing chlorine and aluminum during the friction process, which was hypothesized to be hydrated aluminum chloride. Upon liquefaction, its viscosity resembled that of polyalphaolefins, enabling it to function as a lubricant by reducing the solid surface contact and consequently lowering the COF.

2.5.4. Chemical Vapor Deposition (CVD)

CVD technology has emerged as a critical research focus for developing wear-resistant coatings on aluminum alloys, owing to its superior coating performance and broad applicability. CVD technology significantly enhances the surface properties of aluminum alloys by enabling gaseous precursors to undergo chemical reactions on the substrate surface, leading to the deposition of a protective coating. This process effectively improves their wear resistance, corrosion resistance, and other critical characteristics. In related studies, methods including plasma-enhanced chemical vapor deposition (PECVD), radio frequency chemical vapor deposition (RF CVD), and direct current plasma-assisted chemical vapor deposition (DC PACVD) have been extensively utilized [78–81,122].

PECVD is a critical technique for depositing coatings onto material surfaces. This method leverages plasma to enhance chemical reactions at relatively low temperatures, enabling gaseous precursors to decompose, react, and subsequently deposit onto the substrate surface, forming a coating. PECVD allows for precise control over the composition, struc-

ture, and thickness of the deposited coating, making it widely applicable across numerous fields [78–80].

Li et al., Solomon et al., and Fayed et al. successfully deposited diamond-like carbon (DLC) coatings on aluminum alloy substrates via PECVD technology and investigated their wear resistance properties [78–80]. The research findings indicate that this type of coating possesses the capability to enhance surface wear resistance. The wear resistance of this thin-film coating is influenced by stress shielding and adhesion. Effective stress shielding contributes to the improvement of wear resistance [78]. As illustrated in Figure 14, the wear rate of the DLC-coated samples is reduced by 70%–80% compared to that of the uncoated samples, and the COF decreases from 0.65 to 0.20–0.25, thereby significantly enhancing the wear resistance of the material [79]. Through the bias voltage experiment, it was observed that increasing the bias voltage enhances the proportion of sp^3 bonds in the film, leading to a denser structure. Consequently, this improvement contributes to enhanced mechanical properties and wear resistance of the film. It can be observed from the tribological tests that the film exhibits the lowest COF under a bias voltage of 300V, with the worn surface remaining smooth and free of cracks or spalling [80].

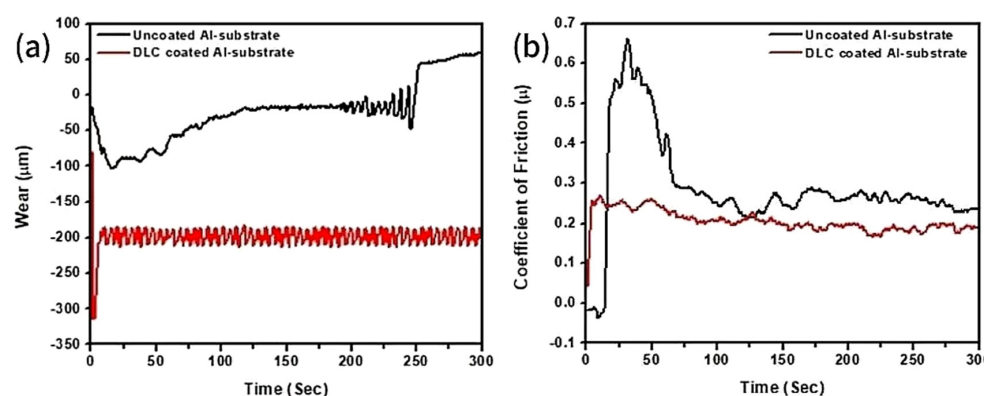


Figure 14. (a) Wear rate for coated and uncoated samples. (b) COF for coated and uncoated samples [79].

RF CVD technology has also been investigated for the preparation of wear-resistant coatings on aluminum alloys. Kyzioł et al. utilized RF CVD technology to modify the surface of 7075 series aluminum-zinc alloys through nitrogen ion implantation and subsequently deposited SiCNH coatings [122]. From the perspective of wear resistance, the coating obtained through this treatment method exhibits a COF as low as 0.09 (under an applied load of 6 mN) with relatively shallow wear tracks, thereby demonstrating superior anti-wear performance. This phenomenon can be attributed to the inherent stability of chemical bonds, such as Si-C and Si-N, which are resistant to breakage during the friction process [123]. Additionally, their microstructure exhibits a compact arrangement with finer grain sizes, leading to a more uniform force distribution and effectively mitigating the local stress concentration.

2.6. Summary of the One-Step Methods

In the field of developing wear-resistant coatings for aluminum alloys, the one-step method is considered to be relatively straightforward and efficient, with numerous alternative approaches also available. The AO equipment is characterized by its simplicity. It leverages the electrochemical principle to combine aluminum ions with oxygen ions, forming an aluminum oxide film at a relatively low cost [86,87]. The MAO equipment builds upon AO by incorporating high-voltage power supplies and other advanced features, utilizing micro-arc discharge to form ceramic films, which incurs slightly higher costs.

Laser-based technologies, such as LSA, employ laser heating to diffuse alloy elements into the substrate, creating an alloy layer. In contrast, LCD uses laser melting to add materials and form a cladding layer on the substrate surface. Both laser techniques involve significant capital investment and relatively high operational costs [51]. Spraying technologies (e.g., PS and CS) encompass spray guns, powder feeding systems, and other components, with costs varying according to the complexity of the technology. Deposition technologies (e.g., ED, EP, PVD, and CVD) require vacuum chambers, gas supply systems, and other specialized equipment. While these deposition methods entail higher initial costs compared to some spraying techniques, they remain more economical than laser-based methods [50].

The advantages of AO include its simplified process and relatively low cost, as well as its ability to effectively enhance the wear resistance and corrosion resistance of aluminum alloys. For instance, a high-pressure hard anodized aluminum coating prepared on 6061 aluminum alloy exhibited a low COF and minimal wear under various lubrication conditions [26]. However, one drawback is that the hardness and thickness of the formed oxide film may not always meet the requirements for high-wear resistance working conditions. Additionally, its electrolyte is corrosive, which can have a certain environmental impact [89–91]. MAO overcomes certain limitations of AO, exhibiting superior properties such as higher hardness and enhanced wear resistance. For example, Louis Rodriguez et al. [25] fabricated hard anodization (HA) and MAO coatings on 5086 aluminum alloy and discovered that the MAO coating demonstrated approximately three times the hardness and elastic modulus of HA. Additionally, the wear rate of the MAO coating was reduced by a factor of 22 compared to HA. The advantages of laser technology include its ability to precisely control the composition and microstructure of coatings, thereby significantly enhancing the surface hardness, wear resistance, and other properties. For instance, Yiming Chi et al. [49] utilized LSA technology to fabricate in situ TiB₂-TiC-reinforced Fe-Al composite coatings on 6061 aluminum alloy. This process resulted in a substantial increase in hardness and a marked reduction in wear-induced volume loss. Nevertheless, the high cost of equipment and the complexity of the process have constrained its large-scale industrial application. Spraying techniques are capable of rapidly melting coating materials and depositing them at high velocities, thereby forming dense and strongly bonded coatings. The AlSi30Cu5 coating prepared by PS refines the β -Si phase, thereby enhancing hardness and wear resistance [57]. Nevertheless, certain technologies, such as SPS, exhibit limited adaptability for large-scale, cost-effective production [56,59]. Deposition techniques enable precise control over the performance of coatings. For example, the CrAlN multilayer coating fabricated via magnetron sputtering not only reduces surface roughness but also enhances hardness and wear resistance [74].

AO and MAO, characterized by their relatively mature processes and favorable cost-effectiveness, have been extensively applied in fields such as aerospace, automotive manufacturing, and electronic equipment [31,32,35,94]. Laser technologies are progressively gaining traction in high-end manufacturing sectors where stringent surface property requirements exist, including the production of aero-engine components [105]. Spraying technology, owing to its high efficiency and material versatility, has found widespread use across industries such as aerospace and automotive engineering [56,59]. Deposition technologies, meanwhile, hold critical importance in domains demanding exceptional coating quality and performance, such as biomedicine, electronics, and automotive manufacturing [74,75,105,119]. Collectively, these technologies serve pivotal roles within their respective domains, thereby facilitating the broad utilization of aluminum alloy materials.

3. Two-Step Methods

Through extensive research on various substrate surface strengthening technologies, researchers have found that the aluminum alloy wear-resistant coatings prepared by a single preparation method still have limitations, such as single performance, poor process adaptability, and limited bonding strength between the coating and the substrate. To address these issues, researchers adopted a two-step approach to develop coatings, which combines the advantages of different techniques and can better cope with the limitations brought about by the one-step method. At present, a series of two-step coating processes have been applied to the surface of aluminum and its alloys. Table 2 details the two-step preparation method and properties of wear-resistant coatings on aluminum and its alloys. Compared with the substrate, the performance of the coating has been significantly improved. This comprehensive method effectively addresses the inherent limitations of the single preparation method and provides a more comprehensive solution for promoting surface strengthening technology.

Table 2. Properties of wear-resistant coatings fabricated on aluminum and its alloys by the two-step method.

Two-Step Method		Substrate			Coating				Ref.
		Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate	
AO + Post-treatment	AO + Ultrasonic Impregnation	ZL109	0.63	6.4×10^{-6} mm ³ /N·m	Nano-MoS ₂ , Al, Si, O	3 µm	0.48	3.4×10^{-6} mm ³ /N·m	[124]
	AO + MAO	6082	-	-	γ-Al ₂ O ₃ , Na, Si, P, K	40–100 µm	0.75–0.83	4.752×10^{-7} mm ³ /N·m	[40]
	AO + ED	6061-T6	0.84	0.66×10^{-2} mm ³ /N·m	AAO, Ni-P	5.51 µm	0.75	0.08×10^{-2} mm ³ /N·m	[125]
	AO + PVD	6061	-	-	MoS ₂ , AAO, Al	50.35–50.4 µm	0.15	1.1×10^{-5} – 2.4×10^{-5} mm ³ /N·m	[126]
MAO + Post-treatment	MAO + Sealing	AA2024	0.9	5.7×10^{-4} mm ³ /N·m	γ-Al ₂ O ₃ , α-Al ₂ O ₃ , Mg, Cu, Si, Na, K, GPTMS, TEOS	19.596 ± 9.192 µm	0.6–0.65	1.66×10^{-6} – 1.86×10^{-6} mm ³ /N·m	[127]
		AA2024-T3	0.6–0.8	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , amorphous alumina, TEOS, GPTMS	11.94 ± 4.7 µm	0.5	-	[128]
		AA2098-T851	0.6–0.8	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , amorphous alumina, TEOS, GPTMS	11.38 ± 4.6 µm	0.6	-	[128]
		2A12	-	-	Al ₂ O ₃ , Paraffin	19.59 µm	0.1–0.2	-	[92]
	MAO + Burnishing	A356	0.4–0.9	-	Al ₂ O ₃ , Graphite, MoS ₂ , Sb ₂ O ₃	33–40 µm	0.08–0.2	-	[129]
		6082	-	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , Pure Graphite, MoS ₂ , Sb ₂ O ₃	26.7 ± 1.6 µm	0.07–0.15	-	[130]
	MAO + VI	2024	-	-	Al, γ-Al ₂ O ₃ , PTFE	56.35 ± 2.1 µm	0.13	7.47×10^{-16} mm ³ /N·m	[131]
	MAO + Silicone Oil Impregnation	6061	0.691 ± 0.060	-	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , 3Al ₂ O ₃ ·2SiO ₂	17 ± 5 µm	0.137 ± 0.016	-	[100]

Table 2. Cont.

Two-Step Method		Substrate			Coating				Ref.
		Alloy Grade	COF	Wear Rate	Composition	Thickness	COF	Wear Rate	
MAO + Post-treatment	MAO + PVD	Untreated Al Alloy	-	-	Al, γ -Al ₂ O ₃ , DLC	-	0.17	-	[132]
		2019Al-Li	0.8	3.01×10^{-2} mm ³ /N·m	Al ₂ O ₃ , SiO ₂ , Mg/Al LDHs	17.9–18 μ m	0.48	3.17×10^{-4} mm ³ /N·m	[133]
	MAO + HS	6063	-	-	MoS ₂ , γ -Al ₂ O ₃ , Mullite Phases	8.8 μ m	0.21	2.94×10^{-7} mm ³ /N·m	[134]
	MAO + PECVD	2A12	0.375	-	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Si-CH ₃ , C-H, Si-O-Si	11.25 μ m	0.23	2.04×10^{-6} mm ³ /N·m	[135]
	MAO + LC	6061	0.59	412.106×10^{-6} mm ³ /N·m	Al, α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Pal	-	0.15–0.43	7.873×10^{-6} mm ³ /N·m	[136]
Other methods		7075	0.35–0.5	-	γ -Al ₂ O ₃ , α -Al ₂ O ₃	15–20 μ m	0.64–0.68	1.22×10^{-6} mm ³ /N·m	[137]
	CS + MAO	2017	0.63	$1.1 \times 10^{-3} \pm 4 \times 10^{-4}$ mm ³ /N·m	α -Al ₂ O ₃ , γ -Al ₂ O ₃ , Si, Na, K	23 $\pm$ 5 μ m	0.65	$7.0 \times 10^{-3} \pm 3 \times 10^{-4}$ mm ³ /N·m	[138]
	EP + PACVD	AA2024-T3	0.8	215×10^{-14} m ³ /N·m	DLC, CNiPCr, Ni-P	56.2–78.2 μ m	0.12	1.8×10^{-17} m ³ /N·m	[139]
	MS + PN	ZL205A	0.75	5.56×10^{-8} g/r·N	TiN, TiN _{0.3} , Al ₃ Ti	24 μ m	0.45	2.49×10^{-8} g/r·N	[140]
	Solution Mixed + EST	AA2028	-	-	UHMWPE, GNPs	96.4 $\pm$ 4.3 μ m	0.18	1.3×10^{-4} mm ³ /N·m	[112]
		A356	0.48	-	α -Al, β -Si, Al ₂ Cu, AlP	600 μ m	0.41–0.44	-	[141]
	PS + LR	6061	-	-	α -Al, β -Si, θ -Al ₂ Cu	-	0.31	1.02×10^{-5} mm ³ /N·m	[142]
	RF PACVD + PVD	7075	-	-	Ti, TiC, a-C:H, TiAl ₃	1 μ m	0.05	9.0×10^{-5} mm ³ /N·m	[143]

Note: AO—Anodic Oxidation; MAO—Micro-Arc Oxidation; ED—Electrodeposition; PVD—Physical Vapor Deposition; VI—Vacuum Impregnation; HS—Hydrothermal Synthesis; PECVD—Plasma-Enhanced Chemical Vapor Deposition; LC—Laser Cladding; CS—Cold Spray; EP—Electroless Plating; PACVD—Plasma-Assisted Chemical Vapor Deposition; MS—Magnetron Sputtering; PN—Plasma Nitriding; EST—Electrostatic Spraying Technology; PS—Plasma Spraying; LR—Laser Remelting; RF PACVD—Radio Frequency Plasma-Assisted Chemical Vapor Deposition.

3.1. AO + Post-Treatment

3.1.1. AO + MAO

AO and MAO are two important metal surface treatment technologies, which play a key role in improving the comprehensive performance of metal materials [128]. The AO process is relatively mature, with simple operation and low cost. By adjusting parameters such as the composition of the electrolyte, temperature, current density, and oxidation time, the thickness, porosity, and hardness of the oxide film can be precisely controlled [124,127]. The oxide film formed by AO has excellent corrosion resistance, insulation, and decorative properties, which can effectively protect the metal substrate and extend its service life. Meanwhile, the oxide film is firmly bonded to the substrate and does not easily fall off. MAO is a surface treatment technology developed on the basis of AO. It utilizes the physical principles of electrochemistry and plasma. Under the actions of high voltage and a large current, the oxide film on the metal surface undergoes micro-arc discharge, thereby forming an oxide film with a special structure and performance [92,132].

Mohedano et al. combined AO and MAO to prepare an alumina-based composite coating on 6082 aluminum alloy [40]. The influences of process parameters such as current density (350–500 mA/cm²) and frequency (50–400 Hz) on the microstructure and tribologi-

cal properties of the coating were systematically studied. The experimental results show that, with the increase in frequency and current density, the coating thickness shows a trend of first decreasing and then increasing. At a low frequency (50 Hz), the thickness of the MAO coating is 100–113 μm , and at a high frequency (400 Hz), the thickness of the MAO coating decreases to 43–54 μm . Pre-anodizing (AO + MAO) can significantly increase the growth rate of the coating (up to 15.6 $\mu\text{m}/\text{min}$), but the final thickness is slightly lower than that of the MAO coating. The low-frequency coating is rich in the $\alpha\text{-Al}_2\text{O}_3$ and mullite phases, with a maximum hardness of $916 \pm 48 \text{ HV}_{0.05}$. The high-frequency coating is mainly composed of $\gamma\text{-Al}_2\text{O}_3$, with a hardness reduced to $447 \pm 46 \text{ HV}_{0.05}$. However, the structure is more uniform and denser, and the porosity decreases from 4.3% to 0.37%. In terms of tribological properties, the wear rate of the coating treated with a high frequency is approximately one order of magnitude lower than that treated with a low frequency. Among them, the wear rate of the A + MAO_400 coating is $4.752 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, which is 89% lower than that of MAO_50 ($4.234 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$). The COF is stable at 0.75–0.83, but the wear trajectory is more uniform. This difference in tribological properties is mainly caused by the synergistic effect of the material structure and the discharge mechanism. Under low-frequency conditions, the long pulse time leads to intense arc discharge, forming a large pancake-like structure and penetrating pores. The hard and brittle $\alpha\text{-Al}_2\text{O}_3$ phase is prone to fragmentation during friction, causing fatigue spalling. Moreover, a large amount of the W element produced by the wear of WC pairs is transferred to the wear surface (12 at.%), intensifying the three-body wear. During high-frequency treatment, short pulses promote the rapid establishment of a “soft spark” regime, forming a sponge-like porous outer layer and a dense intermediate layer. The metastable structure of the $\gamma\text{-Al}_2\text{O}_3$ phase has a certain toughness, and the micro-discharge density increases, making the stress distribution on the coating surface more uniform and reducing crack initiation and propagation. Meanwhile, the 20 μm porous AO film formed by pre-anodic oxidation serves as a transition layer, accelerating the formation of the dense layer at the interface, suppressing excessive oxidation in the arc stage, and making the wear mechanism be mainly characterized by slight abrasive wear. The WC transfer amount is only 0.6 at.%, and the wear trajectory depth decreases from 74.1 μm to 11.9 μm .

3.1.2. AO + ED

ED is based on electrochemical principles. In an electrolyte containing ions of the metal to be plated, the workpiece to be plated serves as the cathode, while the metal to be plated or other insoluble conductors act as the anode. After applying a direct current, the metal ions in the electrolyte gain electrons on the cathode surface and are reduced to metal atoms, depositing to form a uniform coating. The porous alumina layer formed by AO and the ED layer (such as Ni-P) form a mechanical interlocking structure, significantly enhancing the bonding strength between the coating and the substrate, and is not prone to peeling during bending tests. The wear mechanism has shifted from adhesive wear to abrasive wear, with a decrease in the COF, a significant drop in the wear rate, a considerable improvement in wear resistance, and an environmentally friendly and controllable process. It also has the synergistic advantages of hardness and toughness [125].

Chen et al. used AO and ED techniques to prepare Ni-P double coatings on friction stir welding (FSW) joints of 6061-T6 aluminum alloy [125] and studied the effects of the AO intermediate layer (AAO) and ED process parameters on the microstructure and tribological properties of the coating. The coating preparation process is shown in Figure 15. The experimental results show that, compared with the Ni-P coating pretreated with traditional zincate, there is no significant difference in thickness between the AO + ED double coatings (both about 4 μm), the hardness is similar ($413 \pm 1 \text{ HV}$ vs. $417 \pm 1 \text{ HV}$),

and a mechanical interlocking structure between the AAO nanotubes and the Ni-P layer is formed in the structure. The COF decreased from 0.81 to 0.75, and the wear rate decreased from $0.32 \times 10^{-2} \text{ mm}^3/\text{N}\cdot\text{m}$ to $0.08 \times 10^{-2} \text{ mm}^3/\text{N}\cdot\text{m}$ (a decrease of 75%). The differences in tribological properties are mainly caused by the differences in the bonding mode between the coating and the substrate, as well as the wear mechanism. The traditional Ni-P coating is bonded to the substrate through a zincate transition layer, with a relatively weak interfacial bonding force. It is prone to peeling due to stress concentration during friction. The wear mechanism is mainly adhesive wear, accompanied by abrasive wear. The wear trajectory is wide and deep ($780 \mu\text{m} \times 52 \mu\text{m}$), and after the Ni-P layer is penetrated, the substrate directly contacts the counterpart, resulting in large fluctuations in the COF. In the AO + ED double coating, AAO nanotubes ($1.41 \mu\text{m}$) act as the intermediate layer to form a “mechanical lock” structure with the Ni-P layer, significantly enhancing the bonding strength (no obvious peeling in the bending test). During wear, the hard oxide particles (Al_2O_3) of the AAO layer provide support, and the wear mechanism is mainly abrasive wear. The wear trajectory is narrower and shallower ($749 \mu\text{m} \times 19 \mu\text{m}$). Furthermore, the porous structure of the AAO layer can store wear debris, reduce three-body wear, and after the Ni-P layer is worn, the AAO layer can still delay the contact with the substrate, further reducing the wear rate.

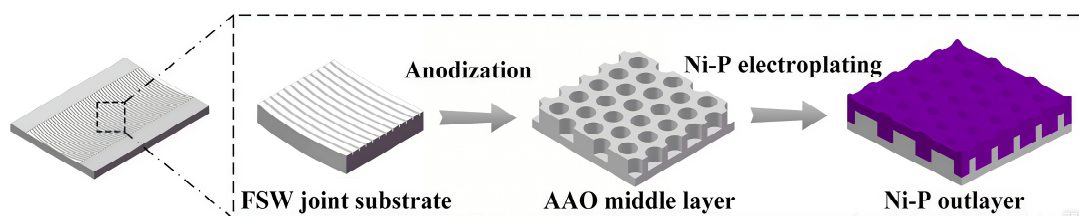


Figure 15. Preparation process of the newly designed duplex Ni-P coating [125].

3.1.3. AO + PVD

PVD is a technique in which materials are vaporized into atoms, molecules, or ionized into ions through physical methods under vacuum conditions and then deposited on the substrate to form a film. This technology mainly includes three methods: vacuum evaporation coating, sputtering coating, and ion plating. By forming a porous anodic oxide film (such as the AAO layer) on the metal surface through AO, its high surface energy and nanotubular structure provide a strong and mechanically interlocked substrate for functional coatings deposited by PVD (such as MoS_2 , DLC, etc.), avoiding the problem of easy peeling of single PVD coatings. The porous structure of the AAO layer can store the lubricating phase (such as MoS_2 nanoflowers), which is continuously released during the friction process to form a self-healing lubricating film, prolonging the lubrication time and reducing the COF. The composite structure optimizes the stress distribution and reduces the wear rate through the synergistic effect of “hard support + soft lubrication” [126].

He et al. employed secondary AO and PVD technologies to fabricate a MoS_2 /porous anodized aluminum oxide/Al composite coating on 6061 aluminum alloy [126]. The effects of sputtering power (50–250 W), temperature (room temperature to 400°C), and film thickness (125–750 nm) on the microstructure and tribological properties of the coating were studied. The experimental results show that, with the increase in sputtering power and the rise in temperature, the coating thickness first increases and then decreases, reaching the optimal state at 350–400 nm. There is no significant change in hardness, but the microstructure changes from worm-like MoS_2 to a uniformly distributed nanoflower-like structure. The tribological performance is manifested as a stable COF of 0.15, the lubrication time is 316.6 times longer than that of the MoS_2 /Al structure, and the wear rate is reduced by approximately 98% (from $5.7 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$ to $1.1 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$).

Figures 16 and 17 indicate that the friction process is divided into three stages: the run-in stage (nanoflowers break to form a transfer film, with a wear rate of $24.0 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$), the stabilization stage (AAO pores continuously release MoS_2 to form a stable lubricating film, with a wear rate as low as $0.48 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$), and the failure stage (after the lubrication is exhausted, the wear of the AAO layer intensifies, and the wear rate rises sharply). The differences in tribological properties stem from the synergistic effect between the porous structure of the AAO layer and MoS_2 nanoflowers; AAO enhances the bonding strength through mechanical interlocking. The MoS_2 stored in its pores is continuously released during friction, forming a low-shear transfer film that disperses stress and prevents direct contact with the substrate. However, the MoS_2/Al structure, lacking support, causes the coating to peel off rapidly, leading to severe adhesive wear. The composite coating significantly enhances the wear-resistant service life through the mechanism of “pore oil storage—structural support—lubrication repair”. The key to reducing the wear rate by 98% lies in the microstructure compatibility between AAO and MoS_2 and the long-term lubrication mechanism.

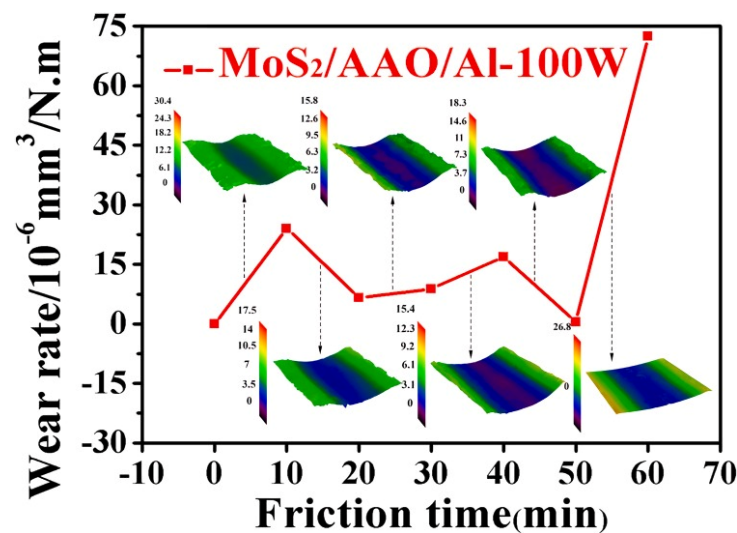


Figure 16. The average wear rate of the $\text{MoS}_2/\text{AAO}/\text{Al}$ composite structure at each friction period [126].

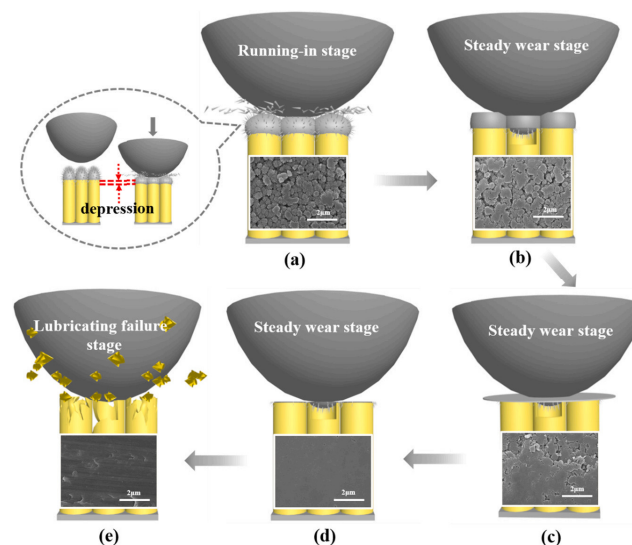


Figure 17. Schematic view for the wear process of the $\text{MoS}_2/\text{AAO}/\text{Al}$ composite structure: (a) Stage I, (b–d) Stage II, and (e) stage III [126].

3.2. MAO + Post-Treatment

3.2.1. MAO + Sealing

MAO technology is based on electrochemical and plasma reactions [92,100,127–136]. The MAO coating can not only significantly enhance the surface hardness of aluminum alloys, effectively resist friction and wear, and reduce the COF and the wear rate but also improve the corrosion resistance of aluminum alloys to a certain extent. The dense layer in the coating can prevent the penetration of corrosive media and delay the occurrence of corrosion [100,127,128,135]. However, there are still some problems with the coatings prepared only by MAO treatment. The main reason is that there are pores and micro-cracks inside it, which will affect the long-term corrosion resistance of the coating. To solve these problems, a subsequent sealing treatment is often adopted. Through sol–gel sealing, the sol–gel solution can penetrate into the pores and micro-cracks of the MAO coating, forming a uniform protective layer and significantly improving the corrosion resistance of the coating [127,128]. The pores can also be sealed and filled with paraffin wax to reduce the invasion of corrosive media and improve the tribological properties of the coating at the same time [92].

Sol–gel-sealed MAO composite coatings were prepared on AA2024 aluminum alloy [127]. The influence of the sol–gel impregnation rates (100 mm/min and 200 mm/min) on the microstructure and tribological properties of the coating was also studied. The experimental results show that, with the increase in impregnation speed, the thickness of the sol–gel coating increases (from 438 ± 21 nm to 696 ± 192 nm). The MAO coating itself has a certain hardness. Sol–gel filling of pores and micro-cracks may enhance the overall mechanical properties. The MAO coating has pores and micro-cracks. It can be covered and filled after sol–gel treatment, and the pores and characteristics are less obvious at 200 mm/min. In terms of tribological properties, the COF of the MAO SG coating (sol–gel-treated MAO coating) is relatively stable at 0.6–0.65, which is lower than that of the MAO coating, and the wear rate is approximately 40% lower than that of the untreated MAO coating. This tribological property difference stems from sol–gel filling pores and micro-cracks, reducing the stress concentration points, lowering the shear stress, and improving wear resistance. From the perspective of the friction mechanism, after filling, the stress distribution on the coating surface is changed, enabling the coating to more evenly disperse the stress and reduce the wear caused by the local stress concentration.

Akbarzadeh et al. prepared sol–gel-sealed MAO coatings on the surfaces of AA2024-T3 and AA2198-T851 aluminum alloys by using sol–gel coating technology [128] and investigated the effects of different aluminum alloy substrates on the microstructure and tribological properties of the coatings. The experimental results show that the MAO coating on AA2024-T3 has more pores, and the MAO coating on AA2198-T851 has more cracks. Sol–gel mainly plays a filling role on the MAO coating of AA2024-T3. The MAO coating of AA2198-T851 is mainly covered by precipitation. In terms of tribological properties, the COFs of the uncoated samples on the AA2024-T3 and AA2198-T851 substrates were 0.6–0.8, while the COFs of the MAO-coated samples varied. After sol–gel treatment, the COF of MAO-A24-S was lower than that of MAO-A24. The COF of MAO-A98-S is similar to that of MAO-A98. This tribological performance difference is due to the different microstructures of MAO coatings on different substrates. The MAO coating of AA2024-T3 has many pores, and the COF is reduced after sol–gel filling. The MAO coating of AA2198-T851 has many cracks, and the sol–gel is difficult to fill effectively, having a relatively small influence on the COF.

A micro-arc oxidation–paraffin composite coating was fabricated on 2A12 aluminum alloy by MAO and paraffin sealing techniques [92], and the influence of paraffin sealing on the microstructure and tribological properties of the coating was studied. The experiment

found that paraffin sealing reduced the porosity of the coating from 1.0489% to 0.3178%, and MAO could increase the hardness. Paraffin wax effectively fills the pores of the MAO coating. Figure 18 shows the surface morphology of aluminum alloy after different treatments and the COFs of four different samples under dry friction and seawater friction. The friction test results indicate that the COF of the composite coating after paraffin sealing was significantly reduced. During the dry friction process, the COF of the MAO sample reached 0.6, and the COF of the paraffin-sealed sample stabilized at 0.2. Under the friction of seawater, the COF of the MAO samples is between 0.35 and 0.4, and the COF of paraffin-sealed samples is approximately 0.1, which is relatively stable. The wear rate of the paraffin-sealed samples is lower than that of the unsealed samples. This difference is due to paraffin filling the pores and forming a lubricating layer at the friction interface, reducing contact and wear. From the perspective of the friction mechanism, the low COF and good lubricity of paraffin reduce the frictional resistance at the friction interface and lower the wear of the material.

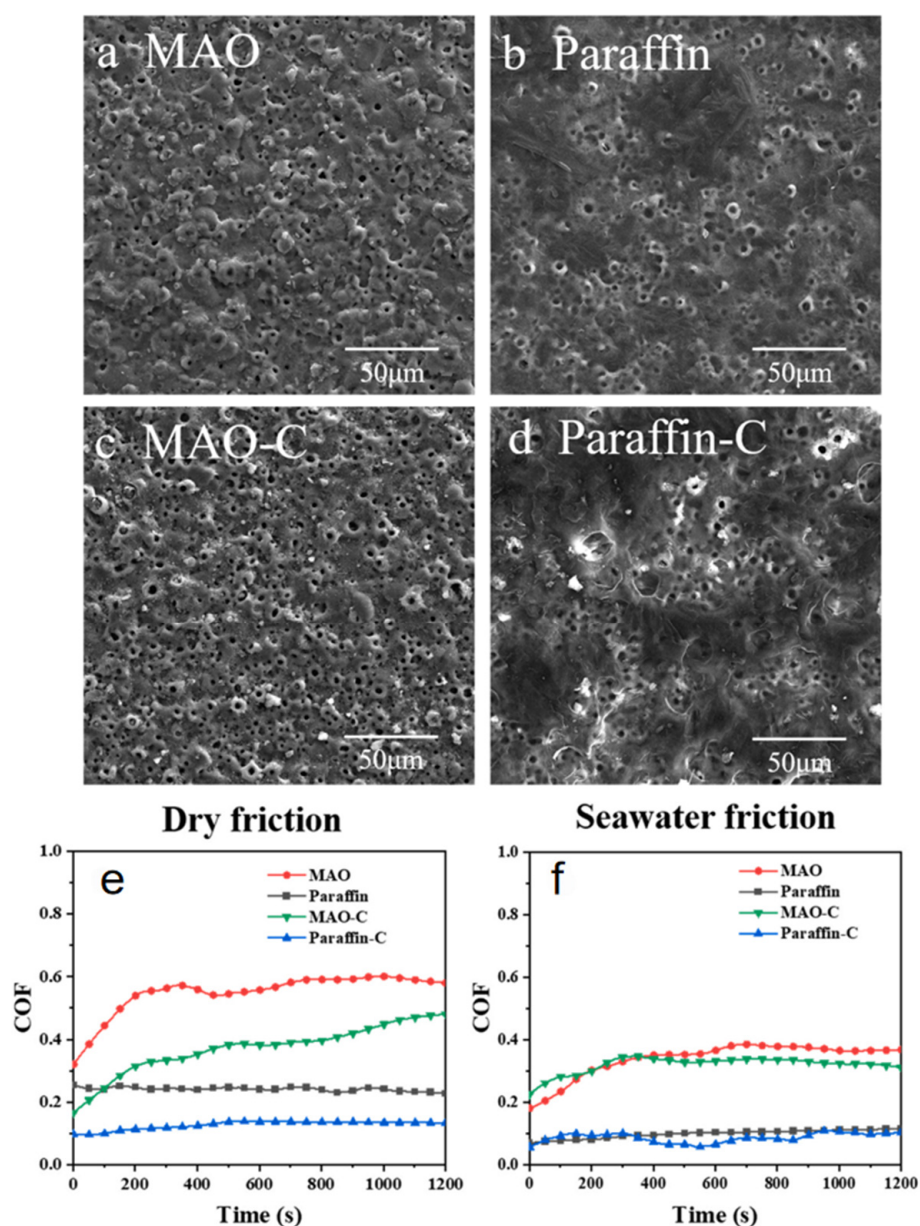


Figure 18. The surface morphology of aluminum alloy after (a) MAO, (b) paraffin, (c) MAO-C, and (d) paraffin-C. COF curves of four different samples under (e) dry friction and (f) seawater friction [92].

3.2.2. MAO + PVD

The combination of MAO and PVD can form a composite structure of “porous ceramic layer + functional deposition layer” on the metal surface. The porous oxide film generated by MAO (such as $\gamma\text{-Al}_2\text{O}_3$) provides mechanical interlocking sites for PVD films (such as DLC), enhancing the bonding strength. Through porous oil storage, wear debris capture, and graphitization induced by PVD film friction, a low shear transfer film is formed, which collaboratively reduces the COF and wear rate, achieving efficient wear resistance of “hard support + soft lubrication”. The process is compatible with the deposition of various metals and functional phases and is suitable for different load and environmental requirements [132].

Jin et al. combined MAO and closed-field non-equilibrium magnetron sputtering (CFUBMS) techniques to prepare porous, textured DLC/MAO multilayer coatings on aluminum alloys [132]. They studied the effects of load (5–60 N) and lubrication conditions (dry friction and oil lubrication) on the microstructure and tribological properties of the coatings. Figure 19 shows the coating preparation process (MAO→DLC deposition). Figure 20 shows the microstructure and composition characterization of MAO and DLC/MAO coatings. The MAO layer forms a porous oxide film through a dual-pulse power supply (positive voltage 290 V, frequency 300 Hz), with micron-sized porous textures and micro-cracks distributed on the surface (Figure 20a). The cross-section indicates that the thickness of the porous layer is approximately 50 μm . The interior is composed of $\gamma\text{-Al}_2\text{O}_3$ (Figure 20c,e). Subsequently, the deposited DLC film (with a thickness of 2 μm) grows in a columnar pattern, fills the MAO pores, and retains the surface texture. The surface roughness is reduced, but the porous feature is retained (Figure 20b,d), forming a “porous support—lubricating cover” composite structure. Under dry friction conditions, with the increase in load, the COF of the DLC/MAO coating decreases from 0.58 (5 N) to 0.19 (30 N), and the width of the wear trajectory reduces by 50.9%. However, the MAO coating has a COF as high as over 0.7 due to the direct contact of the pores with the mating parts, resulting in severe wear. When lubricated with oil, the COF of DLC/MAO further decreases by 13.3–21.4%, and the width of the wear trajectory reduces by 52.1%. Raman spectroscopy confirmed that the DLC membrane had typical D peaks (1365 cm^{-1}) and G peaks (1544 cm^{-1}), with an I_D/I_G value of 1.123, indicating its disordered graphitization structure (Figure 20f). The element distribution shows that there is no obvious element mutation at the interface between the DLC film and the MAO layer, forming a tight mechanical interlock (Figure 20d). X-ray diffraction does not show any new phase, confirming that the DLC deposition does not change the crystal structure of the MAO layer (Figure 20e). Overall, it indicates that the porous texture of the MAO layer captures wear debris and reduces abrasive wear during dry friction. The DLC film forms a low shear transfer film through friction-induced graphitization (with the I_D/I_G value increasing from 1.110 to 1.123), isolating the friction pair. When lubricated with oil, the MAO pores store lubricating oil to replenish the lubricating film, and the high lipophilicity of the DLC surface (contact angle of 5.8°) enhances the solid–liquid synergistic lubrication and inhibits adhesive wear.

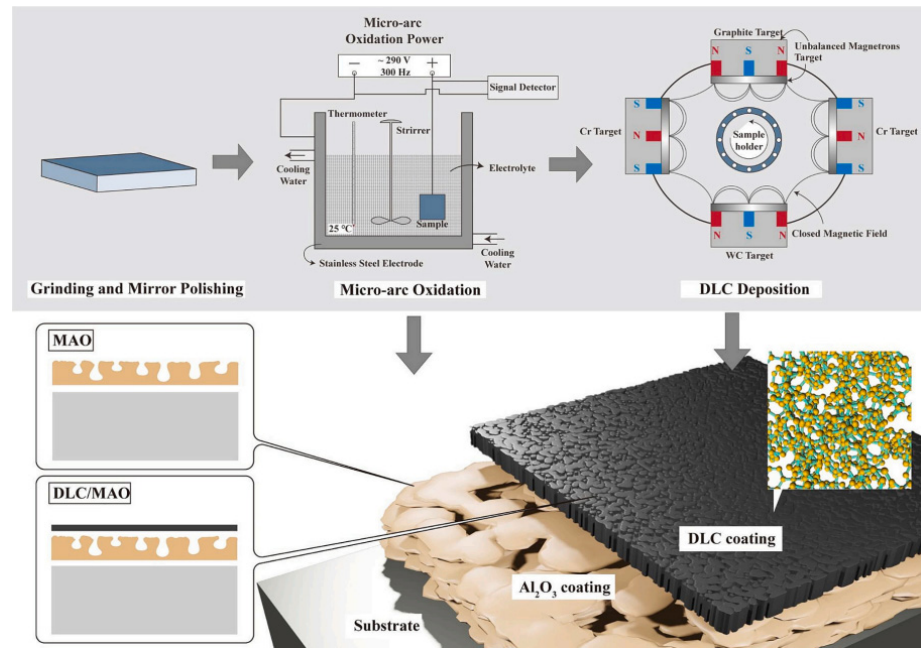


Figure 19. Preparation method of DLC/MAO coating [132].

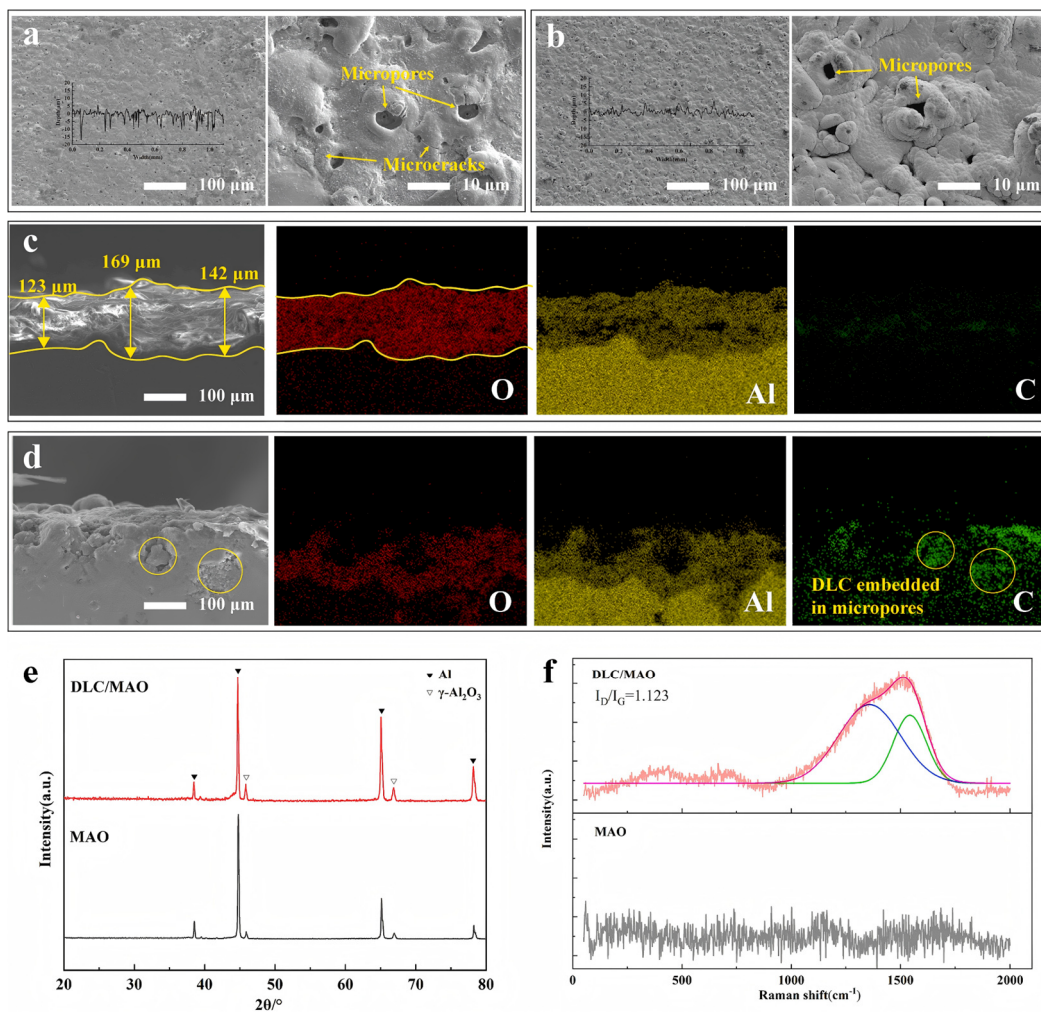


Figure 20. SEM images of (a) MAO coating and (b) DLC/MAO coating. Cross-section morphology and element distribution of (c) MAO coating and (d) DLC/MAO coating. (e) XRD pattern. (f) Raman spectroscopy [132].

3.2.3. MAO + LC

The combination of MAO and LC technologies has shown significant advantages in metal surface modification. Through MAO, porous ceramic layers (such as oxide films containing α -Al₂O₃ and γ -Al₂O₃) are generated on the substrate surface. The rich pores and rough surface provide mechanical interlock sites for LC materials and significantly enhance the bonding strength between the composite coating and the substrate. During the LC process, the functional phases filled in the MAO pores can form a “hard support–soft lubrication” synergistic structure with the ceramic layer, breaking through the performance bottleneck of a single coating and providing an efficient surface strengthening solution with both high load-bearing capacity and low friction for fields such as aerospace and mechanical manufacturing [136].

Sun et al. fabricated composite coatings (MAO-Pal) on 6061 aluminum alloy by using MAO and LC technologies [136] and studied the effects of load, friction velocity, and lubrication conditions on the microstructure and tribological properties of the coating. Experiments show that the MAO layer forms a porous oxide film containing α -Al₂O₃ and γ -Al₂O₃ (with a thickness of approximately 50 μ m, a roughness of 0.78 μ m, and a porosity of 6.28%). After LC, Pal fills the pores with rod-shaped crystal beams, increasing the coating roughness to 0.94 μ m and reducing the porosity to 4.76%, form a “ceramic support–nano-lubrication” structure. The friction test shows that the MAO-Pal COF under dry friction is 0.39 (15.2% lower than MAO and 33.9% lower than the matrix), and the wear rate decreases from $412.106 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ of the matrix to $7.873 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$. The performance is optimal when lubricated with water. When the load is 5 N and the speed is 2.5 cm/s, the COF is as low as 0.3, the width of the wear trajectory is 347.72 μ m, and the lubricating film formed by Pal absorbing water reduces the contact area. Under oil lubrication, the COF is close to MAO (0.15), but the width of the wear trajectory decreases by 52.1%. The performance differences stem from the fact that the porous structure of MAO provides mechanical anchorage for Pal. Its high specific surface area adsorbs the liquid in water/oil to form a lubricating film. During dry friction, Pal dissociates to generate a low shear transfer film, which synergistically inhibits adhesion and abrasive wear. Meanwhile, the low porosity (4.76%) and dense interface delay crack propagation. Ultimately, a significant improvement in tribological performance is achieved.

3.3. Other Methods

3.3.1. CS + MAO

The combination of CS and MAO technologies can prepare composite coatings on metal surfaces such as aluminum alloys, featuring both a high bonding strength and excellent tribological properties [137,138]. Figure 21 is a schematic diagram of the CS + MAO two-phase surface treatment carried out on an aluminum substrate. The CS technology deposits a metal matrix composite coating containing ceramic particles (such as α -Al₂O₃) through high-speed particle impact to form a porous support structure, providing a mechanically interlocked substrate for the subsequent MAO. During the MAO process, the porosity of the CS coating and the content of the ceramic particles affect the growth kinetics of the oxide layer. The low porosity inhibits the thickness of the oxide layer but triggers the advance of the soft spark discharge regime, promoting the generation of the α -Al₂O₃ phase [138]. This composite technology reduces the COF and wear rate through the collaborative path of “structural support—phase composition optimization—wear mechanism regulation”, significantly enhancing the wear resistance and corrosion resistance of the material. It is suitable for the lightweight surface strengthening requirements of the aerospace and automotive industries [137,138].

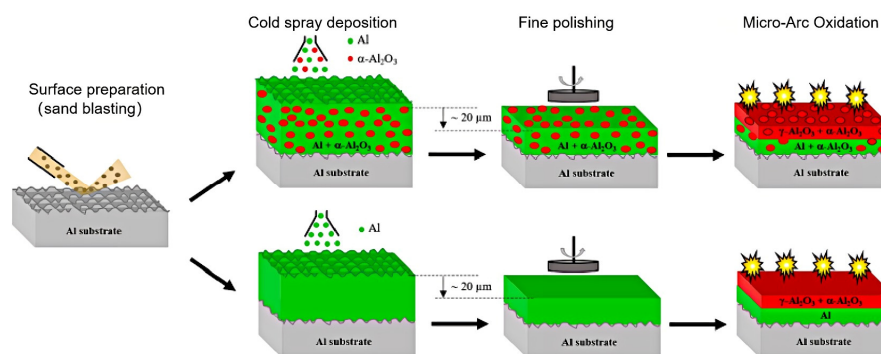


Figure 21. Schematic description of the duplex surface treatments carried out on an aluminum substrate consisting of, first, CS of an Al or an Al/ α -Al₂O₃ composite coating and then followed by MAO [138].

An alumina MAO coating was prepared on 7075 aluminum alloy by CS and MAO technologies [137], and the influence of the MAO treatment process parameter on the microstructure and tribological properties of the coating was studied. The experimental results show that, after MAO treatment, the coating thickness is approximately 15–20 μm , and the hardness reaches 1353 HV_{0.01}. The coating is mainly composed of the γ -Al₂O₃ phase and a small amount of the α -Al₂O₃ phase, presenting a single-layer dense structure with a small number of micropores and micro-cracks. In terms of tribological properties, the COF of the coating after MAO treatment fluctuates within a certain range and then stabilizes, with a wear rate of $1.22 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$. Compared with the untreated cold-sprayed 7075 aluminum alloy, the wear rate is reduced by two orders of magnitude. This difference in tribological properties is mainly caused by the composition and structure of the coating. The MAO coating is mainly composed of Al₂O₃ with a relatively high hardness. During the friction process, its high hardness makes the coating less prone to wear, thereby reducing the wear rate. In addition, the dense structure of the coating reduces the generation and accumulation of wear debris, which also helps to lower the COF. In terms of the friction mechanism, when the MAO coating rubs against the mating part, the Al₂O₃ on the surface plays an anti-wear role, and the smooth surface of the coating reduces the frictional resistance, keeping the COF stable. However, the surface of the untreated cold-sprayed alloy is relatively rough and is prone to generating significant friction and wear during the friction process.

Maizeray et al. employed CS and MAO technologies to fabricate a composite coating containing α -Al₂O₃ particles on 2017 aluminum alloy [138]. The effects of process parameters such as the content of α -Al₂O₃ particles (0, 5, and 14 vol.%); MAO treatment time (20 min and 35 min); and spark discharge mode (arc and soft spark) in the cold spray coating on the microstructure and tribological properties of the coating were studied. With the increase in the content of α -Al₂O₃ particles, the porosity of the cold spray coating decreases, and the thickness becomes thinner. The extension of MAO treatment time leads to an increase in coating thickness, and the coating is thicker and more uniform in the soft spark mode. The α -Al₂O₃ particles are uniformly distributed in the cold spray coating. After MAO treatment, the coating presents a pancake-like structure in the arc mode and a spongy structure in the soft spark mode. Moreover, the α -Al₂O₃ particles undergo morphological transformation in the soft spark mode. The addition of α -Al₂O₃ particles can slightly reduce the COF of the MAO coating and also decrease the wear rate. This tribological property difference is closely related to the material structure. The presence of α -Al₂O₃ particles promotes the formation of the α -Al₂O₃ phase in the MAO coating. This phase has high hardness and helps to reduce the COF. Meanwhile, the structure and porosity of the coating affect its load-bearing capacity and wear mechanism. Although

the sponge-like structure in the soft spark mode is more prone to wear, the overall wear resistance of the coating is still improved due to the presence of $\alpha\text{-Al}_2\text{O}_3$ particles. From the perspective of the friction mechanism, during the friction process, $\alpha\text{-Al}_2\text{O}_3$ particles enhance the anti-wear ability of the coating and alter the generation and distribution of wear debris, thereby affecting the COF and wear rate.

3.3.2. EP + PACVD

PACVD is a technology that uses plasma-activated reactive gases to deposit thin films on the substrate surface at low temperatures, which can precisely control the composition and performance of the films. When combined with EP, a dense metal substrate is first formed through EP (such as a 52 μm thick Ni-P layer) to provide a mechanically interlocked interface. Then, a functional film is deposited by PACVD, and at the same time, plasma bombardment promotes the mutual diffusion of interface elements to form a 4 μm thick CNiPCr gradient layer, enhancing the bonding strength. The composite coating combines the elastic support of the metal base with the wear-resistant and friction-reducing properties of the functional layer. Through the synergistic mechanism of “substrate load-bearing + film anti-wear + interface buffering”, it significantly improves the surface performance of the material and is suitable for wear-resistant and corrosion-resistant scenarios such as aerospace [139].

Staia et al. combined EP and PACVD technologies to prepare a DLC/Ni-P double-layer composite coating on AA2024-T3 aluminum alloy [139] and studied the effects of parameters such as deposition voltage, the carbon–hydrogen ratio, and interface diffusion time on the coating. Experiments show that, with the decrease in deposition voltage, the thickness of the DLC layer increases from 0.9 μm to 1.2 μm , the hardness increases from 7 GPa to 14 GPa, and at the same time, a 4 μm thick CNiPCr diffusion layer is formed between DLC and Ni-P. The Ni-P layer maintains a thickness of 52 μm and a hardness of 7.1 GPa. Tribological tests show that the dry sliding COF of the composite coating is 0.1–0.12, and the wear rate is as low as $1.8 \times 10^{-17} \text{ m}^3/\text{N}\cdot\text{m}$, which is significantly better than that of the substrate (COF 0.5–0.8, wear rate $2.15 \times 10^{-14} \text{ m}^3/\text{N}\cdot\text{m}$) and the Ni-P single-layer coating. The performance difference stems from the synergy of the multilayer structure: The low shear modulus (73 GPa) and high hydrogen content of the DLC layer form a lubricating film, and the friction is reduced by the friction-induced graphitization transfer film under a low load. The CrC gradient layer (elastic modulus 97 GPa) inhibits crack propagation under a high load (5 N), the Ni-P layer provides elastic support (elastic modulus 140 GPa) to prevent substrate deformation, and the CNiPCr diffusion layer alleviates interfacial stress. The friction mechanism is manifested as mainly adhesive wear at low loads, relying on the chemical adsorption and graphitization effects of DLC. A high load turns into abrasive wear. The key to performance improvement is to suppress material loss through the mechanical matching of gradient layers and the bearing capacity of the metal base, as well as the interlayer bonding enhanced by the mutual infiltration of interface elements.

3.3.3. PS + LR

PS technology is a common method for preparing surface coatings. It involves melting and accelerating alloy powder in a high-temperature plasma flame stream, causing it to impact the surface of the substrate to form a coating. LR is a process that uses a high-energy density laser beam to heat a coating, causing part or all of the coating surface to melt and then rapidly solidify, thereby improving the microstructure and properties of the coating. The combination of PS and LR techniques can prepare high-silicon aluminum alloy coatings with excellent performance. The PS technology first prepares a coating on the substrate,

providing a basis for the LR technology. LR technology transforms the wear mechanism of spray coatings from mainly fatigue wear and abrasive wear to mainly slight abrasive wear by eliminating defects, refining the structure, and strengthening the interface. At the same time, it utilizes refined hard phases (primary silicon and eutectic structures) for uniform load-bearing, suppressing the stress concentration and crack propagation and significantly enhancing the wear resistance and service stability of the coating [141,142].

Dong et al. synthesized the Al-20Si/Cu-8P high-silicon aluminum alloy coating on A356 aluminum alloy by using PS and LR technologies [141]. The effects of process parameters such as laser power (2700 W) and scanning speed (10 mm/s) on the microstructure and tribological properties of the coating were studied. The experimental results show that, after LR, the porosity of the coating decreased from 4.3% to 0.2%, the size of the primary silicon was refined from about 10 μm to 5 μm , and the distribution was more uniform. The Cu-8P refiner was fully dissolved and formed an AlP heterogeneous nucleated core, promoting the homogenization of the microstructure. Under dry friction conditions (load 2 N), the COF of the remelted coating is 0.41, and the wear volume is $0.841 \times 10^7 \mu\text{m}^3$, which is 33.1% lower than that of the sprayed coating. The differences in tribological properties result from microstructure optimization: LR eliminates pores and forms metallurgical bonding interfaces. Refined primary silicon and uniformly distributed $\alpha\text{-Al} + \text{Si}$ eutectics act as hard phases, effectively resisting the plowing of the pair. Cu-8P promotes the formation of AlP, refines grains through heterogeneous nucleation, and reduces the stress concentration. Figure 22 shows that there are a large number of adhesive pits, wear debris, and deep and wide furrows on the worn surface of the base material, and the edges are accompanied by fractures and peeling, presenting typical adhesive wear + abrasive wear. The worn surface of the sprayed coating has obvious furrows and a few spalling pits. The wear mechanism is abrasive wear + fatigue wear. The furrows on the worn surface of the remelted coating are shallow and regular, with only a few spalling pits. This is mainly due to the refined and uniform hard phase effectively bearing the load, which inhibits the coating damage. LR significantly improves the wear resistance of high-silicon aluminum alloy coatings.

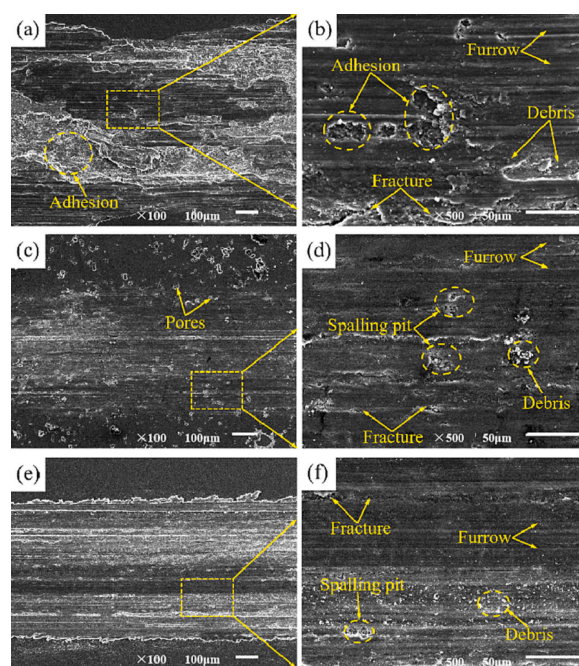


Figure 22. Wear scar SEM morphology: (a,b) substrate; (c,d) sprayed coating; (e,f) remelted coating [141].

A high-silicon aluminum alloy coating of AlSi30Cu5 was prepared on 6061 aluminum alloy by PS technology [142], and the influence of the process parameters on the microstructure and tribological properties of the coating through the LR process (power 3 kW, scanning speed 10 mm/s) was studied. The experiments show that, after LR, the porosity of the coating decreases from 3.66% to 0.37%, the primary silicon distribution is more uniform, and at the same time, a large amount of β -Si and θ -Al₂Cu phases precipitate, forming nanoscale strengthening phases. The wear properties of different coatings are shown in Table 3. Under dry friction conditions (load 5N), the COF of the remelted coating stabilized at 0.31, and the wear rate decreased to $1.02 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$, which was 37.8% lower than that of the sprayed coating. LR eliminates the pores and layered structure of the sprayed coating, forms a metallurgical bonding interface, and reduces the stress concentration. Nanoscale β -Si and θ -Al₂Cu phases are uniformly distributed in the α -Al matrix. As hard points, they effectively resist abrasive grain plowing and simultaneously inhibit crack propagation. Due to the presence of pores and coarse hard phases, the wear of spray coatings is mainly abrasive wear and fatigue wear. However, for remelted coatings, because of the densification of the structure and the homogenization of the strengthening phase, the wear mechanism is mainly slight abrasive wear, and fatigue wear is significantly reduced.

Table 3. Comparison of the wear performance of coatings [142].

	Depth/ μm	Width/ μm	Volume/ μm^3	Wear Rate/ $\times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$
Sprayed	32.96	746.18	5.32×10^7	1.64
Remelted	19.35	666.92	3.29×10^7	1.02

3.3.4. LACE + PTA

Lateral Angular Co-Extrusion (LACE), through a 90° angle extrusion die, enables aluminum and steel to form a metallurgical bond during extrusion, such as embedding steel bars into an aluminum alloy matrix to prepare coaxial composite profiles. The key parameters include the extrusion ratio, punch speed, etc. The intermetallic phase thickness at the interface can be controlled through numerical simulation and is used in the manufacturing of wear-resistant components such as bearing bushings [144]. Plasma Transferred Arc Welding (PTA), which uses a plasma arc to melt alloy powders (such as bearing steel and ceramics) onto the surface of a substrate to form a high-hardness metallurgically bonded coating. For example, cladding AISI 52100 steel on the aluminum substrate effectively improves the microhardness of the coating and is suitable for the preparation of wear-resistant and corrosion-resistant coatings. It is necessary to control the powder parameters to avoid defects such as pores [145].

LACE and the forming process chain were developed by Behrens and Coors et al. through numerical simulation to optimize the extrusion parameters (extrusion ratio 6:1, punch speed 0.5 mm/s), and steel–aluminum composite bearing bushings [144] were fabricated on the surface of AA7075 aluminum alloy. This process reduces the wear rate of the coating by 82% compared with the substrate under a rolling contact load of 60 kN by controlling the intermetallic phase thickness at the interface ($\leq 2 \mu\text{m}$), verifying the load-bearing capacity of the thin steel coating (1.5–2 mm) against tribological loads. Similarly, AISI 52100 bearing steel was cladding on the AISI 1022M aluminum substrate by PTA. After hot-forming and quenching–tempering treatment, the microhardness of the coating reached 880 HV_{0.5}, and the porosity was <1%. Under a contact pressure of 1.8 GPa, the coefficient of friction was stable at 0.18–0.25, and the wear mechanism changed from the adhesive–abrasive wear of the substrate to the slight abrasive wear dominated by the coating [145].

This process chain shares commonalities with the synergy mechanism of the MAO + LC process: The stress distribution is optimized through “hard phase support + interfacial metallurgical bonding”. For instance, the MAO-Pal composite coating prepared by Sun et al. reduced the wear rate by 98% through the collaboration of the porous ceramic layer and the lubricating phase [136], while the LACE-PTA process refined the grains through intermetallic phase control and heat treatment (reducing the average grain size from 50 μm to 15 μm). The wear resistance improvement under heavy load working conditions has been achieved, providing an engineering reference for the lightweight design of aluminum-based bearing components.

3.4. Summary of the Two-Step Methods

The two-step method is a process that combines different surface treatment techniques to improve the surface properties of aluminum alloys. The aim of implementing the two-step method is to address the limitations observed in coatings prepared by the one-step method, including insufficient performance diversity, inadequate process compatibility, and limited bonding strength between the coating and the substrate. Only through the implementation of a complementary two-step process is it possible to prepare coatings with superior friction and wear properties on aluminum and its alloys. This article divides the two-step method into three major categories: AO + post-treatment, MAO + post-treatment, and other combined methods.

Different combinations of the two-step method can meet the diverse demands of aluminum alloys in various application scenarios. For occasions with high requirements for corrosion resistance, the Ni-P layer was electrodeposited on the intermediate layer of anodized aluminum by the “AO + ED” method. By taking advantage of the enhanced adhesion of the AAO layer and the excellent corrosion resistance of the Ni-P layer, it can be used to manufacture aluminum alloy components in fields such as marine engineering and chemical equipment [125]. For applications that pursue a low COF and good lubrication performance, the MoS₂/AAO/Al composite coating prepared by “AO + PVD” has a stable COF at around 0.15, a long lubrication time, and a low wear rate and is suitable for mechanical transmission components, etc. [126].

In addition, the two-step method, which combines different surface treatment techniques, can significantly enhance the comprehensive performance of aluminum alloys. In “MAO + sealing”, the MAO technology forms a multi-oxide phase coating on aluminum alloys, enhancing their hardness and wear resistance. Subsequent sealing treatment can solve the problems of pores and micro-cracks in the coating and improve its corrosion resistance [92,127,128]. In “MAO + PVD”, the MAO layer provides a good adhesion basis for the PVD coating. The functional film deposited by PVD further optimizes the coating performance, making the COF and wear trajectory width of the DLC/MAO coating smaller than those of the MAO coating under dry friction and oil lubrication conditions. This improvement in performance has enabled aluminum alloys to have broader application possibilities in fields with strict requirements for material properties, such as aerospace and automotive manufacturing [132].

4. Summary and Perspectives

Aluminum and its alloys are the most widely used non-ferrous metal structural materials in the industrial field. In the field of wear-resistant coatings for aluminum alloys, the collaborative optimization of lightweight design and structural load-bearing capacity has become a key direction to break through the bottlenecks of traditional applications. As a structural material for machine components, aluminum alloy, through custom forming processes such as topology optimization and additive manufacturing, can effectively enhance

surface hardness, wear resistance, and tensile strength while reducing weight. Combined with coating technologies like MAO and LC, it meets the high load working conditions of aero-engine compressor blades and rail transit bogies. At present, surface techniques aimed at improving the friction and wear characteristics of aluminum and its alloys can be classified into one-step and two-step methods.

Coatings with superior wear resistance can be fabricated on aluminum and its alloys by one-step methods. The salient feature of the one-step method lies in its highly integrated process, user-friendly operation, and relatively straightforward equipment requirements. It eliminates the need for multiple independent sets of equipment, thereby significantly reducing investment costs and conserving space. Furthermore, this method exhibits broad applicability, being compatible with a variety of coating materials and aluminum alloy substrates while offering flexible control over coating thickness and performance. Nevertheless, certain implementations of this method may involve some degree of pollution and fall short of meeting stringent material standards under specific conditions.

Therefore, in the future, the advancement of one-step methods will focus on incorporating environmentally friendly electrolytes into the MAO process and utilizing low-toxicity materials in spray applications to enhance environmental sustainability. This approach aligns with the trend toward green manufacturing. Furthermore, integrating cutting-edge technologies such as artificial intelligence for process optimization and real-time monitoring is anticipated to substantially improve the consistency and efficiency of coatings. Simultaneously, the incorporation of nanomaterials (such as silicon nitride and graphene) into AO/MAO electrolytes or the introduction of composite particles during the spraying/deposition process enables the preparation of multifunctional coatings. These coatings integrate wear resistance and self-lubrication, corrosion resistance, and thermal stability on the surface of aluminum and aluminum alloys, thereby expanding their applications in aerospace, automotive, and high-precision manufacturing fields.

The application of the two-step method has promoted the innovation and development of aluminum alloy surface treatment technology. This has prompted researchers to constantly explore new technological combinations and optimize process parameters to further enhance the coating performance. In “PS + LR” technology, researchers have optimized the LR parameters; reduced the porosity of the high-silicon alloy coating of aluminum alloy; increased its hardness, elastic modulus, and fracture toughness; and lowered the wear rate [141,142]. The development of this technology is conducive to promoting the application of aluminum alloys in emerging fields such as new energy vehicles and electronic devices, providing material support for the development of related industries.

With the improvement of environmental protection requirements, some two-step method combinations that adopt environmentally friendly treatment technologies have greater development potential. For instance, the electrolyte used in the MAO technology of “MAO + post-treatment” is environmentally friendly [127,131,134]. If environmentally friendly sealants are adopted in the subsequent sealing treatment, not only can the coating performance be enhanced but the impact on the environment can be reduced [92,127,128]. This is in line with the concept of sustainable development and is conducive to the green development of the aluminum alloy surface treatment industry, enabling it to be more widely applied in fields with higher environmental protection requirements, such as construction and food packaging.

To sum up, from a technical perspective, AO and MAO in the one-step method form an oxide ceramic coating through electrochemical and plasma discharge. LC and CS rely on energy deposition and high-speed particle impact to achieve the preparation of coatings. Deposition technologies such as PVD, CVD, and ED, on the other hand, construct high-density functional layers, such as DLC and TiN coatings, on the surface of

aluminum-based materials through principles like gas-phase reactions, electrochemical reduction, or sputtering. Two-step methods such as “AO + PVD” and “MAO + sealing” combined processes have optimized the coating performance through process synergy. At the application level, the one-step method has been widely applied in fields such as aerospace structural components and automotive parts due to its advantages of simplicity and efficiency. The two-step method, with its superior comprehensive performance, is better suited for applications like marine engineering and high-end mechanical manufacturing that demand exceptional wear and corrosion resistance. In terms of comparative advantages and disadvantages, the one-step method offers a high degree of process integration but is limited by single-function coatings and insufficient adaptability to complex working conditions. Conversely, the two-step method significantly improves coating hardness, wear resistance, and interfacial bonding strength through complementary processes, albeit at the cost of increased process complexity and extended production cycles. Looking ahead, it is imperative to further investigate green and environmentally friendly processes, such as the development of low-toxicity electrolytes, alongside intelligent technologies, such as AI-driven process parameter optimization, to advance aluminum-based wear-resistant coating technology toward higher performance and multifunctionality.

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