

Article

Study on Microstructure and Wear Resistance Service Characteristics of AlCrN-Coated Relay Injection Mold

Rongchuan Lin, Rongyi Fu, Yipin Wang, Zhihao Chen, Ke Li, Pengcheng Wang, Sheng Lin, Qingmin Huang and Shasha Wei *

College of Marine Equipment and Mechanical Engineering, Jimei University, Xiamen 361021, China; rongchuan@jmu.edu.cn (R.L.); 13338374819@163.com (R.F.); 18350091411@163.com (Y.W.); ccczh18106734@163.com (Z.C.); 18437958277@163.com (K.L.); w2528054036@163.com (P.W.); 17606042921@126.com (S.L.); qmhuang@126.com (Q.H.)

* Correspondence: 200461000025@jmu.edu.cn

Abstract

To address the problem of the short service life of relay injection molds caused by erosion of high-temperature glass fibers, AlCrN coatings were deposited on the surface of ELMAX mold steel using multi-arc ion plating technology. The surface morphology, cross-sectional morphology, and elemental composition of the coatings were analyzed using scanning electron microscopy (SEM) and the attached energy-dispersive X-ray spectroscopy (EDS). The phase structure was characterized by X-ray diffraction (XRD). The surface hardness, film–substrate adhesion strength, and friction and wear performance were tested using a nanoindenter, a scratch tester, and a friction and wear tester, respectively. The effects of duty cycle, arc current, and negative bias voltage on the coating microstructure, hardness, adhesion strength, and friction and wear performance were systematically investigated. Increasing the duty cycle increases surface particles and pits but improves coating density; increasing the arc current increases coating thickness but coarsens particles; increasing the negative bias voltage refines particles but increases pits. Through a three-factor, three-level orthogonal experiment and a multi-index equal-weight weighting method, with hardness, adhesion strength, and friction coefficient as comprehensive evaluation objectives, the optimal process parameters were determined as a duty cycle of 70%, an arc current of 60 A, and a negative bias voltage of 110 V. The optimized coating achieved a hardness of 36.04 GPa (399% higher than that of the uncoated substrate), an adhesion strength of 143.87 N, and a friction coefficient of 0.422. In production cycle tests, the coated mold exhibited an average service life of 128,070 cycles, which is 277% higher than that of the uncoated mold (33,985 cycles). The surface of the coated mold showed only slight scratches, while the uncoated mold exhibited severe glass-fiber plowing grooves. This study provides a process optimization and verification solution for extending the service life of injection molds.



Academic Editor: Kirill A. Emelyanenko

Received: 17 June 2026

Revised: 26 July 2026

Accepted: 28 July 2026

Published: 3 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: AlCrN coating; injection mold; microstructure; service life

1. Introduction

As the core basic component of electronic control systems, the dimensional accuracy and molding stability of relay injection-molded parts directly determine the electrical performance and service reliability of relays [1–3]. During the injection molding production of relays, the mold is subjected to extreme service conditions for long periods: on one hand, high-glass-fiber-reinforced engineering plastics fill the mold at high temperature and high

pressure, causing continuous abrasive wear on the mold cavity, leading to dimensional deviations and excessive product burrs [4–6]; on the other hand, cyclic thermal stress accelerates fatigue failure of the mold surface, ultimately resulting in premature mold scrap. Traditional uncoated molds have short service lives, high maintenance costs, and rapid performance degradation under high-temperature, high-wear conditions, making it difficult to meet the production demands of the relay industry for long durability, high precision, and high stability. Therefore, developing high-performance, wear-resistant coatings specifically for relay injection molds has become a key technical challenge that needs to be urgently addressed [7–12].

Hard coatings for injection mold protection have undergone multiple generations of development. The first-generation coatings are represented by binary nitrides such as CrN and TiN. CrN coatings exhibit good toughness and excellent thermal fatigue resistance, but their hardness is typically only approximately 20 GPa, and the hardness degrades significantly at elevated temperatures, making it difficult to resist the continuous plowing action of glass fibers for prolonged periods. TiN coatings, although possessing relatively high hardness (approximately 25 GPa) and good versatility, have a relatively high friction coefficient (approximately 0.6–0.7) and are susceptible to oxidative softening during high-temperature service, which limits their application in high-temperature injection molding conditions [13–15]. The second-generation coatings introduced Al elements to form ternary nitrides, such as TiAlN and AlCrN, utilizing solid-solution strengthening and age-precipitation effects to significantly enhance hardness and thermal stability. Among these, AlCrN coatings, through the substitutional solid solution of Al atoms into the CrN lattice, achieve a microhardness exceeding 30 GPa and exhibit superior hardness retention and high-temperature oxidation resistance compared to TiAlN at elevated temperatures—rendering them more reliable under the sustained thermo-mechanical coupling conditions of injection molding environments [16,17]. In contrast, although TiAlN exhibits higher initial hardness, its hardness degradation rate is faster during prolonged high-temperature service, and its thermal shock resistance is inferior to that of AlCrN. In recent years, DLC (diamond-like carbon) coatings have attracted attention due to their extremely low friction coefficient (below 0.2), but their poor thermal stability (structural transformation occurs above 300 °C) and weak adhesion to steel substrates make them incapable of withstanding the high temperature, high pressure, and glass-fiber impact during injection molding. Although multilayer PVD coatings (such as CrN/AlCrN or TiN/TiAlN multilayer structures) can balance toughness and hardness, their preparation processes are complex and costly, and stress matching issues at the multilayer interfaces may lead to early delamination failure [18–20]. Considering hardness, high-temperature performance, adhesion strength, and manufacturing cost comprehensively, AlCrN coatings demonstrate the most balanced advantages in the field of injection mold protection and are an ideal candidate for life extension coatings [21,22].

However, during the preparation of AlCrN coatings by multi-arc ion plating, process parameters such as duty cycle, arc current, and negative bias voltage directly determine the coating's microstructure, residual stress, and overall performance [23]. Improper parameter matching can lead to defects such as large particles, pits, and insufficient adhesion, severely affecting the coating's actual service performance on molds. Current research on AlCrN coatings is mostly focused on general cutting tools, while studies on process optimization and performance matching specifically for the service conditions of relay injection molds (high-glass-fiber erosion, thermo-mechanical cyclic coupling) remain scarce. In particular, it should be noted that most existing studies adopt a single indicator (such as hardness or friction coefficient alone) for parameter screening, neglecting the mutual constraints among hardness, adhesion strength, and friction coefficient [24]. Moreover, the lack of service

life verification based on actual production molds results in a significant gap between laboratory optimization results and industrial applications [25].

To address the above issues, this paper focuses on the service requirements of relay injection molds, aiming to improve mold wear resistance and extend service life, and carries out a full-chain study of AlCrN coatings: using duty cycle, arc current, and negative bias voltage as variables, the influence of process parameters on the surface morphology during coating growth is analyzed. A three-factor, three-level orthogonal experiment is designed, with friction coefficient, film-substrate adhesion, and surface hardness as core evaluation indicators, to screen out the optimal preparation process for AlCrN coatings. Subsequently, a comparative injection production cycle test between uncoated molds and molds with AlCrN coating under optimized process parameters is conducted to clarify the performance advantages of the AlCrN coating and quantify the improvement in relay injection mold service life, verifying the industrial application feasibility of AlCrN coatings. This study can provide a theoretical basis and technical support for the life extension design of relay injection molds and promote the large-scale application of coating technology in the field of precision injection molds.

2. Materials and Methods

2.1. Orthogonal Optimization Experiment Design

In this experiment, ELMAX mold steel specimens of size 20 mm × 20 mm × 5 mm were used. The hardness of the specimens before deposition was 7.22 GPa, and the average friction coefficient against a SiC grinding ball was 0.521. A JMU-FCVA600 magnetic filter cathodic arc deposition equipment (JMU-FCVA600 jointly developed by Beijing Normal University and Jimei University, Beijing, China) was used. The cathode arc source was configured with four arc targets, arranged uniformly and alternately distributed on the inner wall of the furnace chamber. The targets were AlCr alloy targets prepared by powder metallurgy, with an Al/Cr ratio of 2. The target purity was 99.9% (3 N). Before deposition, the substrates were polished using 120# to 2000# sandpaper and W2.5 diamond polishing paste and then cleaned with an ultrasonic cleaning device and dried.

The key process parameters in magnetic filter cathodic vacuum arc coating technology include duty cycle, N₂ partial pressure (N₂ flow rate), arc current, negative bias voltage, and deposition temperature. Based on experience, the N₂ flow rate was set to 35 sccm and the deposition temperature to 350 °C. Duty cycle (30%, 50%, and 70%), arc current (40 A, 60 A, and 80 A), and negative bias voltage (90 V, 110 V, and 130 V) were selected as the three factors for a three-level orthogonal experiment. The specific experimental schemes for the orthogonal experiment are shown in Table 1.

Table 1. Orthogonal experiment factor level table.

Test No.	Factor		
	Duty Cycle (A)/%	Arc Current (B)/A	Negative Bias (C)/V
a	1 (30)	1 (40)	1 (90)
b	1	2 (60)	2 (110)
c	1	3 (80)	3 (130)
d	2 (50)	1	3
e	2	2	1
f	2	3	2
g	3 (70)	1	2
h	3	2	3
i	3	3	1

2.2. Microstructure Morphology Analysis Method

In this study, a Phenom-XL scanning electron microscope (SEM, FEI Electron Optics B.V., Eindhoven, The Netherlands) was used to observe the surface morphology of the coatings. To understand the elemental composition distribution of the coatings, semi-quantitative elemental analysis was performed using an energy-dispersive X-ray spectrometer (EDS) attached to the Phenom-XL SEM. By combining morphological observation and elemental analysis, the coating performance was comprehensively evaluated.

2.3. Phase Structure Analysis Method

The phase composition of the coatings was analyzed using a Rigaku Smart Lab X-ray diffractometer (XRD, Rigaku Corporation, Akishima, Tokyo, Japan). The test parameters were set as follows: Cu K α radiation ($\lambda = 0.154$ nm), operating voltage of 40 kV, current of 40 mA, scanning step of 0.02° , and scanning speed of $3^\circ/\text{min}$.

2.4. Surface Hardness Analysis Method

Surface hardness was tested using an NHT2 nanoindenter (Anton Paar GmbH, Graz, Austria) equipped with a Berkovich diamond indenter. The test was performed in load control mode, with a loading rate of 5 mN/min, an unloading rate of 5 mN/min, and a holding time of 10 s. To ensure that the measured results reflected the intrinsic hardness of the coating rather than substrate effects, the maximum indentation depth was set to not exceed 10% of the coating thickness, in accordance with the ISO 14577 standard [26]. For specimens with thinner coatings, a lower maximum load (2 mN) was adopted to ensure that the indentation depth met the above requirement; for specimens with thicker coatings, a maximum load of 5 mN was used. Five test points were randomly selected for each specimen, and the hardness values were calculated from the unloading curves according to the Oliver–Pharr method, with the arithmetic mean taken as the final hardness value.

2.5. Adhesion Strength Analysis Method

Coating adhesion was tested using a WS-2005 nanoindenter (Lanzhou Zhongke Kaihua Technology Development Co., Ltd., Lanzhou, China) by scratch testing. The adhesion strength of the coatings was characterized by the indentation method. The load at which obvious coating damage (such as delamination, cracking, etc.) began to occur was defined as the critical load, denoted as L_C . The critical load value was selected to represent the adhesion strength of the coating. The test parameters were as follows: load range 0–150 N, scratch speed 5 mm/min, and loading speed 100 N/min.

2.6. Friction and Wear Analysis Method

Friction and wear tests were performed using an HT-600 friction (Lanzhou Zhongke Kaihua Technology Development Co., Ltd., Lanzhou, China) and wear tester, with the average friction coefficient of the coatings as the primary evaluation indicator. The test employed a SiC grinding ball with a diameter of 5 mm as the counterbody material, with an applied load of 30 N, a rotational speed of 400 r/min, and a sliding duration of 30 min. After the test, the wear morphologies were further analyzed by SEM and EDS.

2.7. Production Cycle Comparison Method

In this study, an ARBUEDO MARS-3A170 (Zhejiang Arbueo Intelligent Equipment Manufacturing Co., Ltd., Taizhou, China) injection molding machine was used for production cycle testing of relay components. The mold had two cavities (one mold, two cavities). For each test, one cavity of the mold was coated with AlCrN, while the other cavity was left uncoated as a control. The part flash height was inspected every 5000 cycles, and a flash height ≥ 0.1 mm was used as the criterion for mold failure. Four repeated verification tests

were conducted under the same mold and molding material conditions, and the average value was taken as the mold service life.

3. Results

3.1. Coating Surface Elemental Analysis

The surface atomic contents of the AlCrN coating specimens are shown in Table 2. The Al/Cr ratio of the targets used in the experiment was 2, but the Al/Cr ratios of all nine groups of coatings were less than 2, indicating that the segregation phenomenon occurred. The Al/Cr ratios of groups a, d, and g ranged from 0.93 to 1.09; those of groups b, e, and h ranged from 1.13 to 1.17; and those of groups c, f, and i were 1.27. This indicates that the Al/Cr ratio is more closely related to the process parameter of arc current, and the Al/Cr ratio gradually increases with increasing arc current.

Table 2. Surface elemental composition of the nine groups of AlCrN specimens.

Test No.	Al/at%	Cr/at%	N/at%	Al/Cr
a	26.91	27.87	45.23	0.97
b	29.58	25.27	45.15	1.17
c	30.50	24.10	45.40	1.27
d	25.95	27.87	46.19	0.93
e	29.93	26.40	43.67	1.13
f	31.08	24.39	44.53	1.27
g	27.55	25.38	47.07	1.09
h	29.64	25.77	44.59	1.15
i	31.43	24.74	43.83	1.27

3.2. Coating Phase Structure Analysis

The surface XRD patterns of the AlCrN coating specimens are shown in Figure 1. From the diffraction patterns, it can be observed that all nine groups of coatings deposited under different process parameters exhibited phases such as CrN, AlN, and the substrate, showing generally similar trends. Variations in process parameters did not cause significant changes in the diffraction peak intensities.

During the coating deposition process, the concentration of active atoms on the coating surface was significantly higher than that in the interior. This is mainly attributed to the strong diffusivity of active nitrogen atoms, which readily penetrate the coating and react with metal atoms to form stable CrN and AlN phases. In some diffraction patterns, the AlN (200) and CrN (111) diffraction peaks were not observed. This may be because the deposition time was relatively short, and the active nitrogen atoms did not fully react with Al and Cr atoms to form these phases.

3.3. Coating Surface Morphology Analysis

From the SEM surface morphologies shown in Figure 2, it can be observed that all nine groups of AlCrN coatings exhibit typical arc evaporation deposition surface characteristics, with the main defect types being white particles (droplet condensates) and light-colored pits (particle detachment or back-sputtering traces) on the surface. Comparing the images of each group, it can be observed that when the duty cycle increases from 30% (groups a, b, and c) to 70% (groups g, h, and i), the distribution density of white particles and pits on the surface visually shows an increasing trend. As the arc current increases from 40 A (groups a, d, and g) to 80 A (groups c, f, and i), the size of the particles significantly enlarges, and the dimensions of the pits also expand accordingly. When the negative bias voltage increases from 90 V (groups a, e, and i) to 130 V (groups c, d, and h), the particle size of the white particles decreases, but the number of pits visually increases. These phenomena can be respectively attributed to the following: increasing the duty cycle shortens the

pulse off-time, leading to insufficient cooling of arc spots and intensified target material splashing; increasing the arc current results in higher arc spot energy and more intense molten splashing while also increasing the probability of large particle detachment forming pits; increasing the negative bias voltage enhances ion bombardment energy, increasing the probability of particles being sputtered and removed, but the strong bombardment also tends to cause local back-sputtering, forming pits. It should be noted that, due to the limitations of SEM image resolution and sample size considerations, this study did not perform quantitative image statistical analysis on particle size distribution, areal density, or pit area fraction. The above visual observation trends are only intended as a qualitative reference for the influence of process parameters on surface morphology.

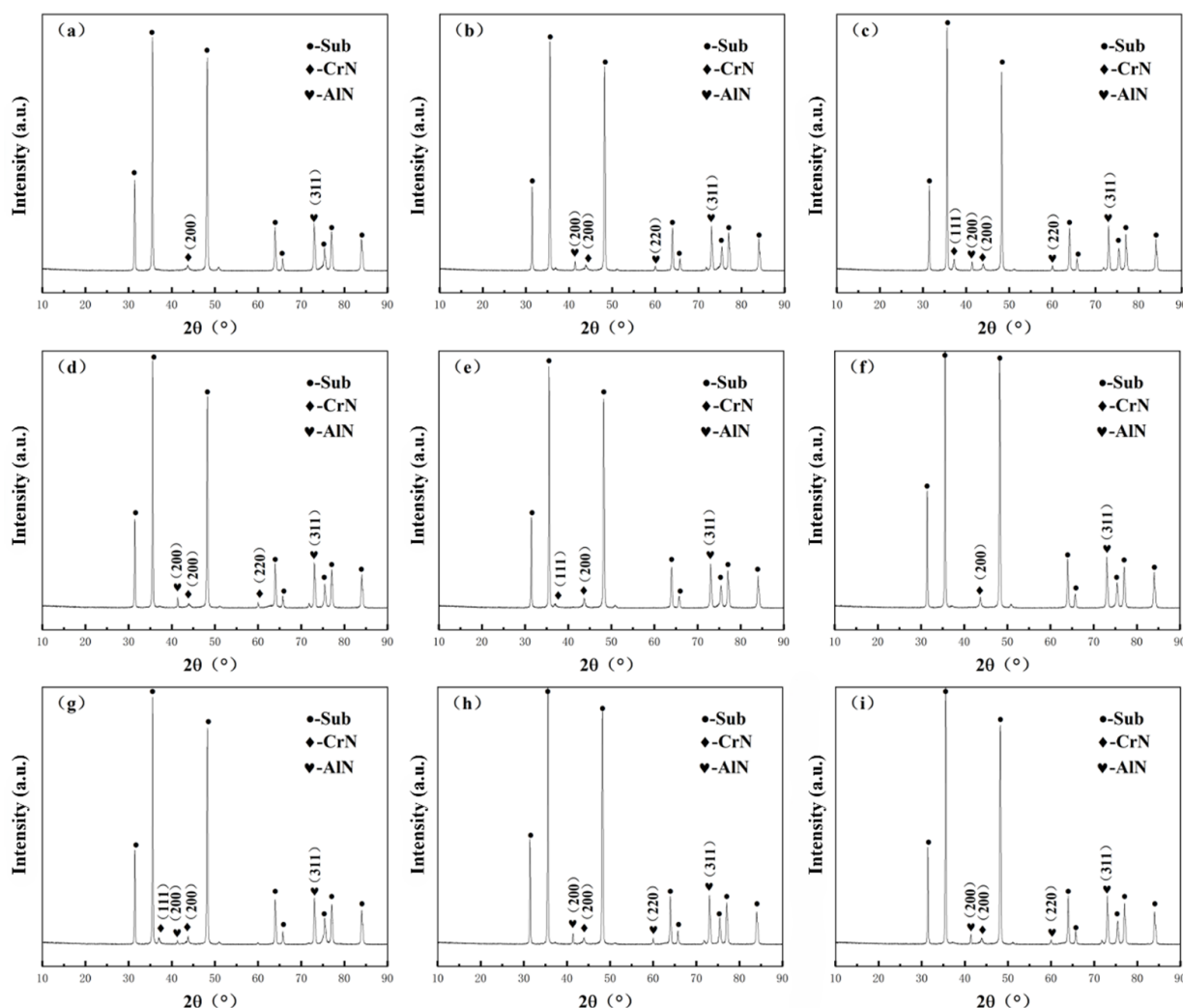


Figure 1. XRD patterns of the nine groups of AlCrN coating specimens: (a) Specimen a; (b) Specimen b; (c) Specimen c; (d) Specimen d; (e) Specimen e; (f) Specimen f; (g) Specimen g; (h) Specimen h; (i) Specimen i.

Figure 3 shows the cross-sectional morphologies of the nine groups of AlCrN coating specimens observed under a scanning electron microscope. The coating thicknesses of the AlCrN specimens are shown in Table 3. Specimens a, d, and g all have an arc current of 40 A, and their coating thicknesses are significantly thinner than those of the other specimens, indicating that the arc current is strongly correlated with coating thickness, and increasing the arc current correspondingly increases the coating thickness. Specimens g, h, and i have a duty cycle of 70%; the cross-sections of these three specimens are denser and

smoother compared to the other specimens, indicating that a higher duty cycle significantly contributes to the improvement of coating density.

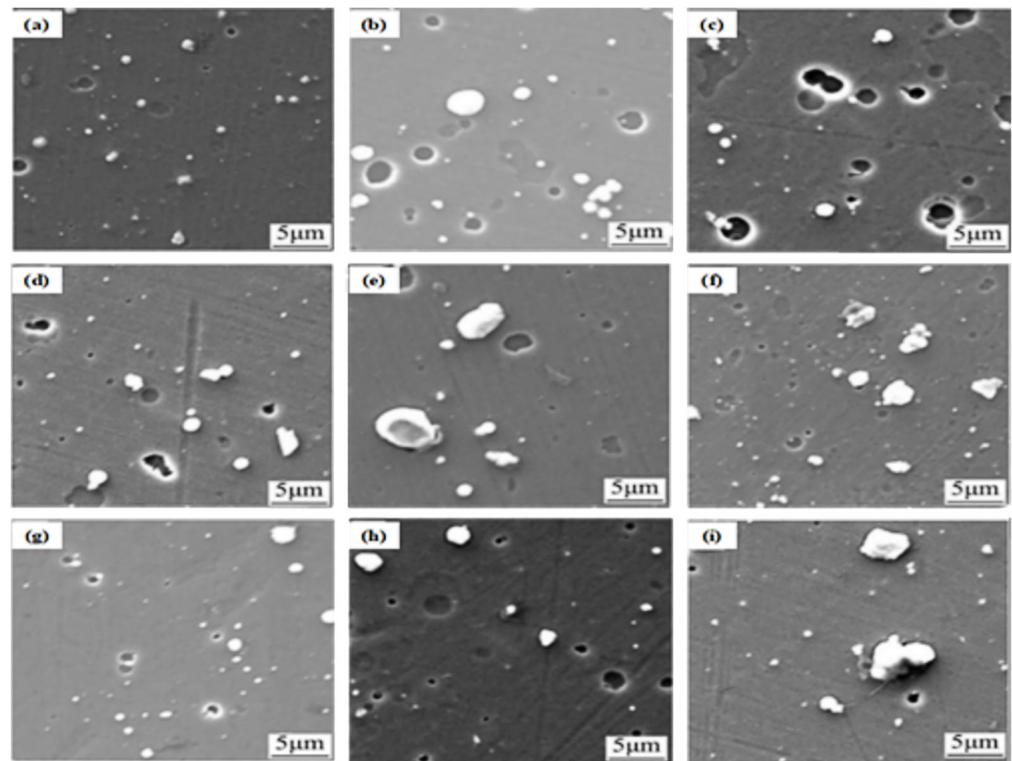


Figure 2. Surface morphologies of nine groups of AlCrN coating specimens: (a) Specimen a; (b) Specimen b; (c) Specimen c; (d) Specimen d; (e) Specimen e; (f) Specimen f; (g) Specimen g; (h) Specimen h; (i) Specimen i.

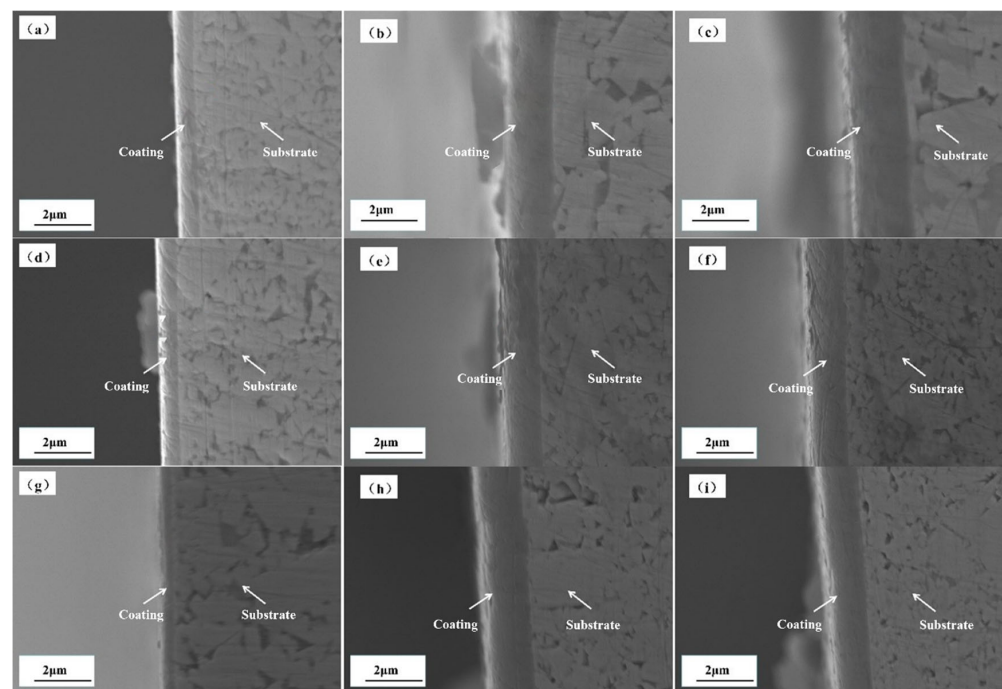


Figure 3. Cross-sectional morphologies of AlCrN coatings of the nine groups of specimens: (a) Specimen a; (b) Specimen b; (c) Specimen c; (d) Specimen d; (e) Specimen e; (f) Specimen f; (g) Specimen g; (h) Specimen h; (i) Specimen i.

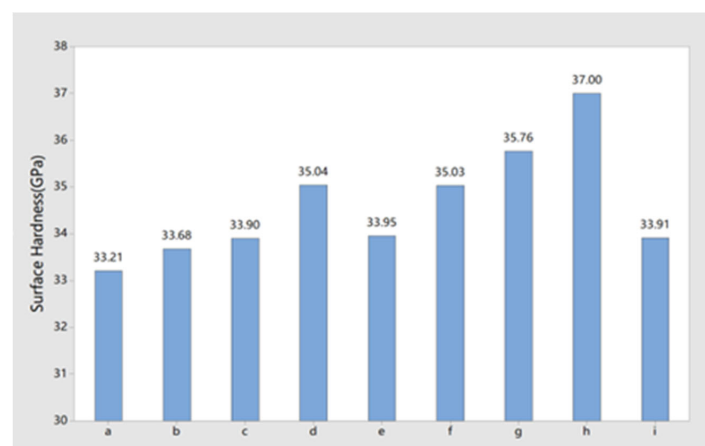
Table 3. Coating thicknesses of the nine groups of AlCrN coating specimens.

Test No.	a	b	c	d	e	f	g	h	i
Coating thickness	0.73	1.72	2.09	0.75	1.27	1.36	0.45	1.77	1.14

3.4. Coating Performance Analysis

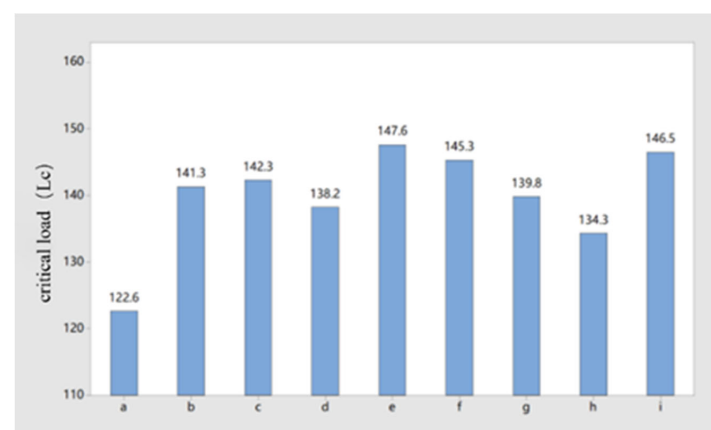
3.4.1. Coating Surface Hardness Analysis

The surface hardness of the nine groups of specimens is shown in Figure 4. After deposition of AlCrN coatings on the substrate surface, the surface hardness of the substrate increased from 7.22 GPa to a range of 33.21 GPa to 37.00 GPa. The duty cycle had a more significant effect on coating hardness; as the duty cycle increased from 30% to 70%, the coating hardness increased. This is mainly attributed to the fact that a higher duty cycle increases the deposition rate and energy input per unit time, promoting coating densification and thereby significantly improving the coating hardness.

**Figure 4.** Comparison of surface hardness of the nine specimens.

3.4.2. Adhesion Strength Analysis

The critical loads of the nine groups of specimens are shown in Figure 5. Specimens a, d, and h exhibited critical loads below 139 N, indicating that the adhesion strengths of the coatings in these three groups were the poorest. Specimens b, c, and g showed critical loads around 140 N, indicating that the adhesion strengths of the coatings in these three groups were good. Specimens e, f, and i exhibited critical loads exceeding 145 N, indicating that the adhesion strengths of the coatings in these three groups were the best.

**Figure 5.** Adhesion strength of AlCrN coatings from the nine groups of specimens.

3.4.3. Friction and Wear Results Analysis

The instantaneous friction coefficient curves and the average friction coefficients of the nine groups of specimens are shown in Figure 6 and Table 4, respectively. In the early stage of the test, the friction coefficient rose sharply and then gradually stabilized as the test progressed, which is attributed to the initial increase caused by surface contaminants. After calculation, the average friction coefficients of the nine groups of AlCrN coating specimens were 0.581, 0.543, 0.586, 0.538, 0.496, 0.532, 0.435, 0.446, and 0.486, respectively.

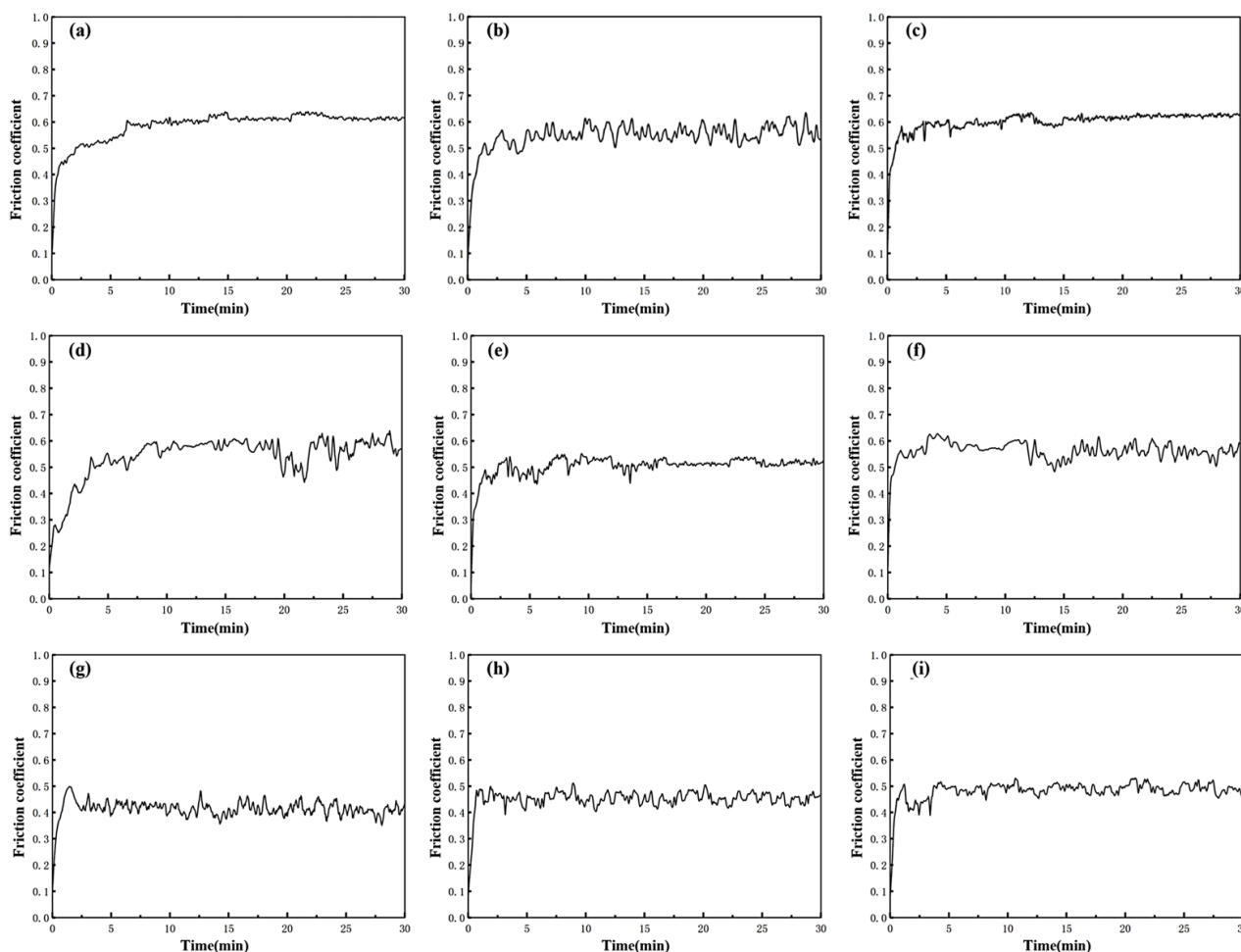


Figure 6. Friction coefficient curves of the nine groups of specimens: (a) Specimen a; (b) Specimen b; (c) Specimen c; (d) Specimen d; (e) Specimen e; (f) Specimen f; (g) Specimen g; (h) Specimen h; (i) Specimen i.

Table 4. Average friction coefficients of the nine groups of AlCrN coating specimens.

Test No.	a	b	c	d	e	f	g	h	i
Average friction coefficient	0.581	0.543	0.586	0.538	0.496	0.532	0.435	0.446	0.486

Figure 7 Friction and wear morphologies of the nine groups of AlCrN coating specimens. Wear tracks of varying widths appeared on the specimen surfaces. To further analyze the wear types, two points within the wear tracks were selected for EDS analysis.

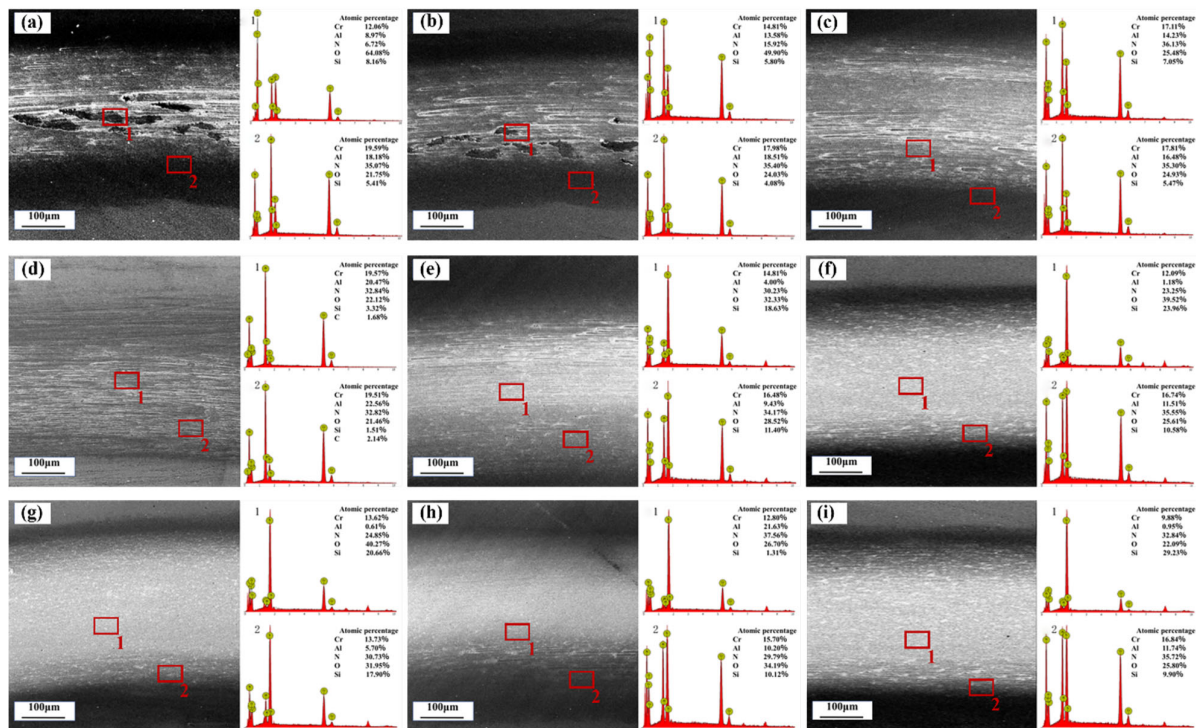


Figure 7. Surface wear morphologies of the nine groups of AlCrN coating specimens: (a) Specimen a; (b) Specimen b; (c) Specimen c; (d) Specimen d; (e) Specimen e; (f) Specimen f; (g) Specimen g; (h) Specimen h; (i) Specimen i.

Fine particles were observed on the worn surfaces of all specimens, exhibiting characteristics of abrasive wear. EDS analysis detected the presence of elements originating from the SiC ball as well as oxygen on the surfaces of all AlCrN coating specimens, indicating that adhesive wear and oxidative wear occurred during the sliding process. For specimens a, b, and c, the wear debris was mainly distributed in the central region, accompanied by a large amount of adhered material. EDS analysis showed that the oxygen content in these specimens was significantly higher than that in the other specimens, indicating that these specimens suffered the most severe oxidative wear.

By comparison, it was found that increasing the duty cycle reduced the wear of the AlCrN coating specimens. This may be attributed to the fact that coatings deposited at higher duty cycles can achieve superior oxidation resistance and wear resistance, effectively suppressing the occurrence of wear.

3.5. Orthogonal Experimental Results and Analysis

3.5.1. Orthogonal Experimental Results

After conducting hardness tests, adhesion strength tests, and friction and wear tests on the specimens, range analysis was performed on the results to determine the degree of influence of each factor on the performance indicators of the AlCrN coatings, as well as the optimal schemes. As can be seen from the tables, the optimized process parameters derived from the individual analysis of each indicator are inconsistent. Therefore, it is necessary to comprehensively consider the primary and secondary influences of the factors to determine the optimal coating process parameters. The individually optimized parameters for each performance indicator are summarized as follows: surface hardness, adhesion strength, and average friction coefficient. The orthogonal experimental results are shown in Table 5.

Table 5. Orthogonal experiment results.

Test No.	A	B	C	H	B	f
	Duty Cycle	Arc Current	Negative Bias	Hardness /GPa	Adhesion /N	Avg. Friction Coefficient
a	1	1	1	33.21	122.6	0.581
b	1	2	2	33.68	141.3	0.543
c	1	3	3	33.90	142.3	0.586
d	2	1	3	35.04	138.2	0.538
e	2	2	1	33.95	147.6	0.496
f	2	3	2	35.03	145.3	0.532
g	3	1	2	35.76	139.8	0.435
h	3	2	3	37.00	134.3	0.446
i	3	3	1	33.91	146.5	0.486

3.5.2. Range Analysis of Coating Surface Hardness

To study the influence of each parameter on hardness, range analysis was performed on the hardness results. K_1 , K_2 , and K_3 are the average hardness values for each of the three levels of each influencing factor. The R value reflects the maximum range among K_1 , K_2 , and K_3 . The results are shown in Table 6.

Table 6. Range analysis of surface hardness from orthogonal experiment.

Level	A	B	C
	Duty Cycle	Arc Current	Negative Bias
K_1	33.60	34.67	33.69
K_2	34.67	34.88	34.82
K_3	35.56	34.28	35.31
R	1.96	0.60	1.62

The range R indicates the magnitude of the influence of the factor on hardness, and the K value indicates the influence of each level on hardness. The results in Table 6 show that the ranking of parameters influencing surface hardness is duty cycle > negative bias voltage > arc current. The optimal process scheme for surface hardness is $A_3B_2C_3$, i.e., a duty cycle of 70%, an arc current of 60 A, and a negative bias voltage of 130 V.

3.5.3. Range Analysis of Adhesion Strength

The range R indicates the magnitude of the influence of the factor on adhesion strength, and the K value indicates the influence of each level on adhesion strength. The results in Table 7 show that the ranking of parameters influencing adhesion strength is arc current > duty cycle > negative bias voltage. The optimal process scheme for adhesion strength is $A_2B_3C_2$, i.e., a duty cycle of 50%, an arc current of 80 A, and a negative bias voltage of 110 V.

Table 7. Range analysis of film-substrate adhesion strength in the orthogonal experiment.

Level	A	B	C
	Duty Cycle	Arc Current	Negative Bias
K_1	135.4	133.5	138.9
K_2	143.7	141.1	142.1
K_3	140.2	144.7	140.6
R	8.3	11.2	3.2

3.5.4. Range Analysis of Average Friction Coefficient

The range R indicates the magnitude of the influence of the factor on the average friction coefficient, and the K value indicates the influence of each level on the average friction coefficient. The results in Table 8 show that the ranking of parameters influencing

the average friction coefficient is duty cycle > arc current > negative bias voltage. The optimal process scheme for the average friction coefficient is $A_3B_2C_2$, i.e., a duty cycle of 70%, an arc current of 60 A, and a negative bias voltage of 110 V.

Table 8. Range analysis of the average friction coefficient from the orthogonal experiment.

Level	A	B	C
	Duty Cycle	Arc Current	Negative Bias
K_1	0.570	0.518	0.521
K_2	0.522	0.495	0.509
K_3	0.456	0.535	0.518
R	0.114	0.040	0.012

3.6. Process Parameter Optimization

Using the range analysis of the orthogonal experiment and an equal-weight multi-index weighting method, the three core indicators were subjected to multi-objective optimization to determine the optimal process parameters. Surface hardness and adhesion strength are higher-is-better indicators (higher values correspond to better coating performance), while the friction coefficient is a lower-is-better indicator (lower values correspond to better coating performance). H_{norm} , B_{norm} and f_{norm} are the normalized values of hardness, adhesion strength, and friction coefficient, respectively. S is the equal-weight weighted score. The formulas are as follows:

Higher-is-better normalization formula:

$$x_{ij,norm} = \frac{x_{ij} - x_{j,min}}{x_{j,max} - x_{j,min}} \quad (1)$$

Lower-is-better normalization formula:

$$x_{ij,norm} = \frac{x_{j,max} - x_{ij}}{x_{j,max} - x_{j,min}} \quad (2)$$

Equal-weight weighted comprehensive score:

$$S_i = \frac{1}{m} \sum_{j=1}^m x_{ij,norm} \quad (3)$$

x_{ij} : original measured value of the j -th indicator for the i -th test;

$x_{j,max}$: maximum value of the j -th indicator among all tests;

$x_{j,min}$: minimum value of the j -th indicator among all tests;

$x_{ij,norm}$: normalized value of the j -th indicator for the i -th test;

m : number of performance evaluation indicators (in this paper, $m = 3$: surface hardness, adhesion strength, average friction coefficient);

S_i : comprehensive score for the i -th test.

Calculations were performed according to the formulas, and the comprehensive scores for the nine tests are shown in Table 9.

The average scores per level in the orthogonal experiment are shown in Table 10. Using the equal-weight weighted comprehensive score S , the average score per level G was further calculated, and G was used as the indicator for selecting the optimal level (a larger G indicates better coating performance).

Table 9. The multi-index weighted scores from the orthogonal experiment.

Test No.	Normalized Hardness	Normalized Adhesion	Normalized Friction Coeff	Comprehensive Score
	H_{norm}	B_{norm}	f_{norm}	S
1	0	0	0.0331	0.0110
2	0.1240	0.7480	0.2848	0.3856
3	0.1821	0.7880	0	0.3234
4	0.4828	0.6240	0.3179	0.4749
5	0.1953	1	0.5960	0.5971
6	0.4802	0.9080	0.3576	0.5819
7	0.6728	0.6880	1	0.7869
8	1	0.4680	0.9272	0.7984
9	0.1847	0.9560	0.6623	0.6010

Formula for average score per level:

$$G_{x,t} = \frac{1}{z} \sum_{i \in (x,t)} S_i \quad (4)$$

S_i : comprehensive score of the i -th test ($i = 1, 2, 3 \dots 9$);

x : any factor under consideration (A: duty cycle, B: arc current, C: negative bias);

t : the t -th level of factor x ($t = 1, 2, 3$);

z : number of times each level of factor x appears repeatedly in the test (in this paper, $z = 3$);

$G_{x,t}$: average comprehensive score of the t -th level of factor x .

Table 10. Average scores per level from orthogonal experiment.

Factor	Avg. Score Level 1	Avg. Score Level 2	Avg. Score Level 3	Optimal Level
	$G_{x,1}$	$G_{x,2}$	$G_{x,3}$	
A ($G_{A,t}$)	0.240	0.551	0.729	A_3 (70%)
B ($G_{B,t}$)	0.424	0.594	0.502	B_2 (60 A)
C ($G_{C,t}$)	0.403	0.585	0.532	C_2 (110 V)

In summary, the optimized deposition process parameters for AlCrN are a duty cycle of 70%, an arc current of 60 A, and a negative bias voltage of 110 V. Specimens were trial-produced using the optimized process parameters and tested for surface hardness, adhesion strength, and average friction coefficient. The results are shown in Table 11. Compared to untreated specimens, the surface hardness increased by 399%, the adhesion strength was at a relatively high level among the other nine specimens, and the average friction coefficient was at a relatively low level among the nine specimens. The theoretical performance of the coating was significantly improved compared to before optimization.

Table 11. Performance of AlCrN coating with process parameters optimized by orthogonal experiment.

Performance Indicator	Result
Coating thickness	1.38 μm
Surface hardness	36.04 GPa
Adhesion strength	143.87 N
Average friction coefficient	0.422

3.7. Injection Production Cycle Comparison

The service lives of AlCrN-coated molds and uncoated molds were compared on a relay component mold with two cavities (one mold, two cavities). Molds in experiments 1, 3, 5, and 7 were coated with AlCrN using the optimal deposition process parameters, while

molds in experiments 2, 4, 6, and 8 were left uncoated as the control group. The part flash height ≥ 0.1 mm was used as the criterion for mold failure. Four identical experiments were performed for each condition, and the average values were taken. The comparison of the service life between the AlCrN-coated and uncoated molds is shown in Table 12.

Table 12. Comparison of service lives between AlCrN-coated and uncoated molds.

Test No.	1	2	3	4	5	6	7	8
Failure cycle number	128,740	34,580	121,020	36,660	128,940	32,720	133,580	31,980
Average service life of AlCrN-coated mold	128,070							
Average service life of uncoated mold	33,985							

In the experiments, specimens 1, 2, 3, 4, 5, 6, 7, and 8 were produced under the same conditions. When the uncoated specimens 2, 4, 6, and 8 reached cycle counts of 34,580, 36,660, 32,720, and 31,980, respectively, the produced parts exhibited flash heights of 0.122 mm, 0.118 mm, 0.132 mm, and 0.126 mm, exceeding the part control standard. Therefore, molds 2, 4, 6, and 8 were judged to have failed. The Figure 8 shows a comparison of the surface wear conditions between the AlCrN-coated molds and the uncoated molds when specimens 2, 4, 6, and 8 failed. The surfaces of the uncoated molds exhibited severe glass-fiber plowing grooves, while the surfaces of the AlCrN-coated molds only showed slight scratches, minor pitting on the edges, and slight sinking. The wear resistance of the AlCrN-coated molds was significantly better than that of the uncoated mold cavities.

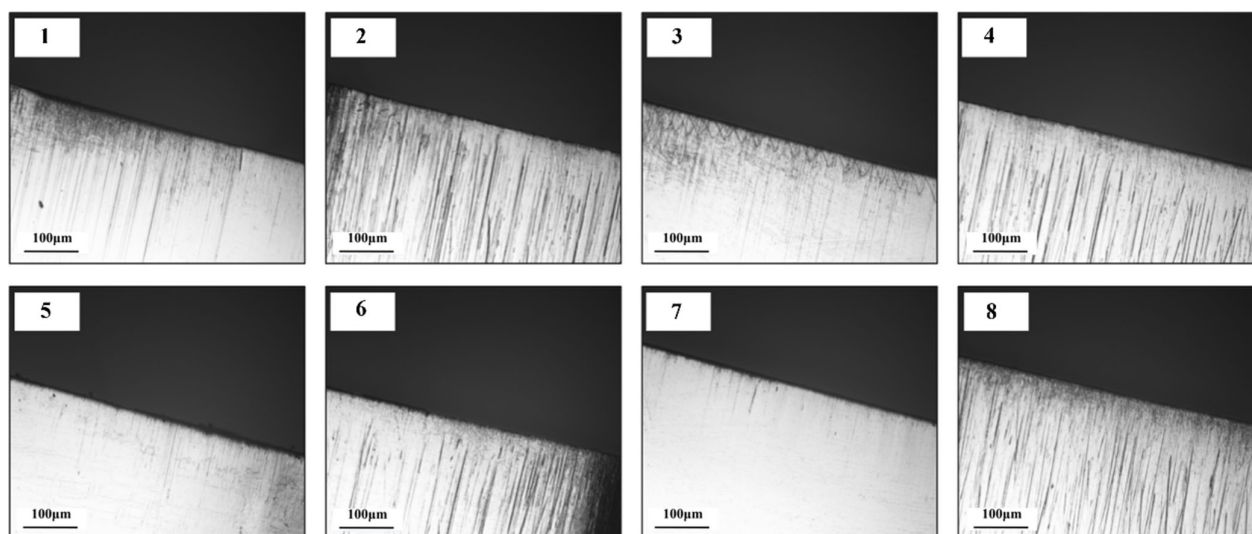


Figure 8. Comparison of surface wear conditions between AlCrN-coated molds and uncoated molds (1–8) upon failure of specimens (2), (4), (6), and (8).

The non-failed molds 1, 3, 5, and 7 continued to be produced. When they reached cycle counts of 128,740, 121,020, 128,940, and 133,580, respectively, the produced parts exhibited flash heights of 0.118 mm, 0.123 mm, 0.112 mm, and 0.128 mm, exceeding the part control standard, and were therefore judged as failed. The test ended at this point. Based on the average service life, the AlCrN coating extended the mold service life by approximately 277%.

4. Discussion

In this study, increasing the duty cycle improved coating density and hardness but also increased surface defects. This is consistent with the results of Singh et al. using pulsed arc

ion plating; however, in HiPIMS (High-Power Impulse Magnetron Sputtering) technology, a low duty cycle instead resulted in higher hardness, indicating that the underlying mechanism of duty cycle effects differs fundamentally depending on the deposition technique [27]. The arc current showed a strong positive correlation with coating thickness, but excessively high arc current led to particle coarsening and an increased number of pits and exerted the greatest influence on adhesion strength. Ahmad et al. also found that the optimal adhesion strength was achieved at an arc current of 80 A [28]. Increasing the negative bias voltage refined the particles and enhanced hardness, but excessive bias voltage reduced adhesion strength due to over-bombardment, which is consistent with the findings of Gilewicz et al., who also confirmed the existence of an optimal bias voltage range [29].

Compared with similar coatings reported in the literature, the optimized coating in this study achieved a hardness of 36.04 GPa, which is at a relatively high level for AlCrN coatings, approaching the 37.5 GPa reported for HiPIMS processes and significantly superior to the 17–23.6 GPa obtained by conventional cathodic arc evaporation. The adhesion strength of 143.87 N is substantially higher than the 73.3–108 N reported in the literature, which may be attributed to the high surface quality of the ELMAX substrate and the multi-index optimization strategy [30,31]. The friction coefficient of 0.422 is also at a relatively low level. These comparisons indicate that, through reasonable multi-index orthogonal optimization, comprehensive performance close to that of advanced processes can be achieved on conventional multi-arc ion plating equipment [32].

In the injection molding cycle tests, the coated mold exhibited a 277% improvement in service life, which is mainly attributed to a triple mechanism: the high hardness (36.04 GPa) effectively resists abrasive plowing by glass fibers; the high adhesion strength (143.87 N) ensures that the coating does not delaminate under cyclic thermal stress; and the low friction coefficient (0.422) reduces interfacial shear forces, thereby decreasing the wear rate [33]. This improvement is at the upper end of the 2–3 times range reported in industrial practice, validating the engineering effectiveness of the optimized scheme. However, this study did not address high-temperature oxidation performance or thermal fatigue resistance and was limited to a single mold product. Future work should be extended to a wider range of injection molding conditions and coating systems.

5. Conclusions

During the preparation of AlCrN coatings by multi-arc ion plating, the duty cycle, arc current, and negative bias voltage significantly influenced the coating structure and properties. Increasing the duty cycle improved coating density and hardness but also increased surface defects. Increasing the arc current increased the coating thickness but caused particle coarsening. Increasing the negative bias voltage refined the particles but increased the number of pits, while the adhesion strength increased first and then decreased with increasing negative bias voltage.

Through a three-factor, three-level orthogonal experiment and a multi-index equal-weight weighting method, the optimal process parameters were determined as a duty cycle of 70%, an arc current of 60 A, and a negative bias voltage of 110 V. The optimized coating achieved a hardness of 36.04 GPa (an increase of 399%), an adhesion strength of 143.87 N, and a friction coefficient of 0.422.

Production cycle verification demonstrated that the AlCrN-coated mold achieved an average service life of 128,070 cycles, representing a 277% improvement over the uncoated mold (33,985 cycles). The coated mold surface exhibited only slight scratches, while the uncoated mold showed severe glass-fiber plowing grooves.

Through the synergistic effects of high hardness for abrasive wear resistance, high adhesion strength for interfacial delamination resistance, and low friction coefficient for

friction reduction, the AlCrN coating significantly extended the service life of relay injection molds under high-temperature glass-fiber erosion conditions. This study provides a quantifiable process optimization scheme and industrial validation data for extending the service life of injection molds.

It should be noted that the evaluation of the friction and wear performance of the coatings in this study was primarily based on the friction coefficient, SEM observation of wear morphologies, and EDS elemental analysis. Quantitative indicators such as wear track profilometry (e.g., wear track width, depth, wear volume, and specific wear rate) were not assessed. Therefore, the discussion on the improvement of wear resistance remains predominantly qualitative and lacks comprehensive quantitative wear data support. This limitation is mainly attributed to the constraints of experimental equipment and testing conditions. Relevant quantitative characterization will be further improved in subsequent studies.

Author Contributions: Conceptualization, R.F.; methodology, Y.W. and Z.C.; formal analysis, K.L. and P.W.; writing—original draft preparation, R.F. and S.L.; writing—review and editing, S.W.; supervision, R.L.; project administration, R.L.; funding acquisition, R.L. and Q.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the University–Industry Cooperation Project of Fujian Province (Grant No. 2022H6030) and the Fujian Provincial Science and Technology Plan Guiding Project (Grant No. 2023H0014).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

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

References

- Kim, M.; Jeon, J.; Rhee, B.; Turng, L.S.; Choi, J.H.; Gim, J. Elimination of halo gloss transition surface defects on injection-molded parts. *Sci. Rep.* **2026**, *16*, 11629. [[CrossRef](#)]
- Frumosu, F.D.; Ronsch, G.O.; Kulahci, M. Mould wear-out prediction in the plastic injection moulding industry: A case study. *Int. J. Comput. Integr. Manuf.* **2020**, *30*, 1245–1258. [[CrossRef](#)]
- Bergstrom, J.; Thuvander, F.; Devos, P.; Boher, C. Wear of die materials in full scale plastic injection moulding of glass fibre reinforced polycarbonate. *Wear* **2001**, *251*, 1511–1521. [[CrossRef](#)]
- Hopmann, C.; Bobzin, K.; Brögelmann, T.; Orth, M.; Kruppe, N.; Naderi, M. Replication of micro-structured injection molds using physical vapor deposition coating and dynamic laser mold tempering. *J. Polym. Eng.* **2018**, *38*, 315–322.
- Chang, Y.Y.; Weng, S.Y.; Chen, C.H.; Fu, F.X. High temperature oxidation and cutting performance of AlCrN, TiVN and multilayered AlCrN/TiVN hard coatings. *Surf. Coat. Technol.* **2017**, *332*, 494–503. [[CrossRef](#)]
- Chang, Y.Y.; Huang, K.C. Improvement of Tribological Performance of TiAlNbN Hard Coatings by Adding AlCrN. *Materials* **2022**, *15*, 7750. [[CrossRef](#)] [[PubMed](#)]
- Du, H.; Wang, L.L.; Young, M.Q.; Zhao, H.B.; Xiong, J.; Wan, W.C. Structure and properties of lanthanum doped AlCrN coatings. *Surf. Coat. Technol.* **2018**, *337*, 439–446. [[CrossRef](#)]
- Ji, C.C.; Guo, Q.Q.; Li, J.P.; Guo, Y.C.; Yang, Z.; Yang, W.; Xu, D.P.; Yang, B. Microstructure and properties of CrN coating via multi-arc ion plating on the valve seat material surface. *J. Alloys Compd.* **2022**, *891*, 161966. [[CrossRef](#)]
- Daure, J.L.; Voisey, K.T.; Shipway, P.H.; Stewart, D.A. The effect of coating architecture and defects on the corrosion behaviour of a PVD multilayer Inconel 625/Cr coating. *Surf. Coat. Technol.* **2017**, *324*, 403–412. [[CrossRef](#)]
- Lukaszewicz, K.; Sendor, J.; Paradecka, A.; Pawlyta, M.; Chmiela, B.; Pancielejko, M.; Szczucka-Lasota, B.; Wegrzyn, T.; Tanski, T. Structure and Tribological Properties of AlCrN plus CrCN Coating. *Coatings* **2020**, *10*, 1084. [[CrossRef](#)]
- Chen, M.H.; Wu, D.Q.; Chen, W.L.; Zhang, S.H. Structural optimisation and electrochemical behaviour of AlCrN coatings. *Thin Solid Films* **2016**, *612*, 400–406. [[CrossRef](#)]

12. Nguyen, H.C.; Joska, Z.; Pokorný, Z.; Studeny, Z.; Sedlák, J.; Majerík, J.; Svoboda, E.; Dobrocky, D.; Procházka, J.; Tran, Q.D. Effect of Boron and Vanadium Addition on Friction-Wear Properties of the Coating AlCrN for Special Applications. *Materials* **2021**, *16*, 4651.
13. Endrino, J.L.; Fox-Rabinovich, G.S.; Reiter, A.; Veldhuis, S.V.; Galindo, R.E.; Albella, J.M.; Marco, J.F. Oxidation tuning in AlCrN coatings. *Surf. Coat. Technol.* **2007**, *201*, 4505–4511. [[CrossRef](#)]
14. Liu, J.; Wang, Y.C.; Liu, G.Q.; Hua, J.F.; Deng, X. Properties and Performance of TiAlSiN and AlCrN Monolayer and Multilayer Coatings for Turning Ti-6Al-4V. *Coatings* **2023**, *13*, 1229. [[CrossRef](#)]
15. Liu, J.; Mei, H.J.; Hua, J.F.; Wang, J.; Wang, Y.C.; Yi, G.M.; Deng, X. High-Temperature Oxidation and Wear Resistance of TiAlSiN/AlCrN Multilayer Coatings Prepared by Multi-Arc Ion Plating. *Nanomaterials* **2025**, *15*, 503. [[CrossRef](#)] [[PubMed](#)]
16. Michalczewski, R.; Kalbarczyk, M.; Slomka, Z.; Osuch-Slomka, E.; Luszcz, M.; Liu, L.; Antonov, M.; Hussainova, I. Sliding Wear Performance of AlCrN Coating on TiB₂/Ti Composites at High Temperatures. *Int. J. Mater.* **2021**, *14*, 6771. [[CrossRef](#)] [[PubMed](#)]
17. Mo, G.W.; Yu, H. Study on the tribological properties of AlN/AlCrN composite coatings on the surface of TA15 alloy. *Alex. Eng. J.* **2026**, *135*, 266–272. [[CrossRef](#)]
18. He, D.Q.; Feng, Z.H.; Zheng, W.W.; Li, W.S.; Shang, L.L.; Zhai, H.M.; Cheng, B.; Zhang, X.J. Post-deposition annealing effects on microstructure, mechanical and tribological properties of AlCrN films. *J. Mater. Res. Technol.* **2023**, *25*, 6843–6852. [[CrossRef](#)]
19. Beake, B.D.; Endrino, J.L.; Kimpton, C.; Fox-Rabinovich, G.S.; Veldhuis, S.C. Elevated temperature repetitive micro-scratch testing of AlCrN, TiAlN and AlTiN PVD coatings. *Int. J. Refract. Met. Hard Mater.* **2017**, *69*, 215–226. [[CrossRef](#)]
20. Tsai, D.C.; Huang, R.H.; Chang, Z.C.; Chen, E.C.; Huang, Y.L.; Shieu, F.S. Substrate Bias-Driven Structural and Mechanical Evolution of AlCrN and AlCrSiN Coatings via Reactive Magnetron Sputtering. *Materials* **2025**, *18*, 1671. [[CrossRef](#)] [[PubMed](#)]
21. Soranansri, P.; Dubois, A.; Moreau, P.; Funazuka, T.; Dohda, K.; Dubar, L. Tribological Performance of AlCrN, TiAlN, and Arc-DLC Coatings in Hot Forming of Aluminum Alloy. *Lubricants* **2025**, *13*, 430. [[CrossRef](#)]
22. Aktarer, S.M.; Sert, Y.; Küçükömeroglu, T. Investigation of structural, hardness, adhesion, and tribological properties of CrN and AlCrN coatings deposited on cylinder liner. *Mater. Des.* **2025**, *253*, 113972. [[CrossRef](#)]
23. Zheng, J.; Zhou, H.; Gui, B.H.; Luo, Q.S.; Li, H.X.; Wang, Q.M. Influence of Power Pulse Parameters on the Microstructure and Properties of the AlCrN Coatings by a Modulated Pulsed Power Magnetron Sputtering. *Coatings* **2017**, *7*, 216. [[CrossRef](#)]
24. Adesina, A.Y.; Iqbal, Z.; Al-Badour, F.A.; Gasem, Z.M. Mechanical and tribological characterization of AlCrN coated spark plasma sintered W-25%Re-HfC composite material for FSW tool application. *J. Mater. Res. Technol.* **2019**, *8*, 436–446. [[CrossRef](#)]
25. Singh, A.; Ghosh, S.; Aravindan, S. Investigation of oxidation behaviour of AlCrN and AlTiN coatings deposited by arc enhanced HIPIMS technique. *Appl. Surf. Sci.* **2020**, *508*, 14812. [[CrossRef](#)]
26. ISO 14577-1; Metallic Materials—Instrumented Indentation Test for Hardness and Materials Parameters. International Organization for Standardization: Geneva, Switzerland, 2002.
27. Gilewicz, A.; Jędrzejewski, R.; Mysliński, P.; Warcholinski, B. Structure, Morphology, and Mechanical Properties of AlCrN Coatings Deposited by Cathodic Arc Evaporation. *J. Mater. Eng. Perform.* **2019**, *28*, 1522–1531. [[CrossRef](#)]
28. Jokar, K.; Elmkhah, H.; Fallah-Lalehzari, A.; Fattah-alhosseini, A. Impact of duplex plasma nitriding and AlCrN coating on mechanical, tribological, and corrosion properties of H13 tool steel. *J. Mater. Res. Technol.* **2026**, *41*, 1804–1813. [[CrossRef](#)]
29. Warcholinski, B.; Gilewicz, A.; Mysliński, P.; Dobruchowska, E.; Murzynski, D. Structure and Properties of AlCrN Coatings Deposited Using Cathodic Arc Evaporation. *Coatings* **2020**, *10*, 793. [[CrossRef](#)]
30. Lacki, P.; Wieckowski, W.; Luty, G.; Wiczorek, P.; Motyka, M. Evaluation of Usefulness of AlCrN Coatings for Increased Life of Tools Used in Friction Stir Welding (FSW) of Sheet Aluminum Alloy. *Materials* **2020**, *13*, 4124. [[CrossRef](#)] [[PubMed](#)]
31. Ahmad, F.; Zhang, L.; Zheng, J.; Sidra, I.; Zhang, S.H. Characterization of AlCrN and AlCrON Coatings Deposited on Plasma Nitrided AISI H13 Steels Using Ion-Source-Enhanced Arc Ion Plating. *Coatings* **2020**, *10*, 306. [[CrossRef](#)]
32. Kumar, C.S.; Patel, S.K. Effect of chip sliding velocity and temperature on the wear behaviour of PVD AlCrN and AlTiN coated mixed alumina cutting tools during turning of hardened steel. *Surf. Coat. Technol.* **2018**, *334*, 509–525. [[CrossRef](#)]
33. Hopmann, C.; Bobzin, K.; Brögelmann, T.; Schäfer, C.; Schöngart, M.; Röbig, M.; Naderi, M. Improved molding of micro structures using PVD-coated mold inserts. *J. Polym. Eng.* **2016**, *36*, 575–582. [[CrossRef](#)]

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