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INVESTIGATION OF IMPROVING WEAR RESISTANCE AND SERVICE LIFE OF DIES BASED ON MODERN TECHNOLOGIES

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ABSTRACT

This study investigates methods to enhance the wear resistance and service life of stamping dies used in automotive sheet metal forming, with a focus on galvanic cobalt alloy coating technology. Die wear represents a critical problem in modern manufacturing, directly affecting part quality and production costs. Experimental research was conducted using SKD 11 (Japanese) die steel coated with galvanic cobalt alloys at various electrolyte temperatures (40–70°C) and cathode current densities (60–70 A/dm²). Mathematical regression models were developed to optimize coating hardness and adhesion. Results demonstrate that cobalt coatings applied at 55°C with cathode current density of 60–70 A/dm² achieve the highest wear resistance—approximately 3.5 times greater than coatings deposited at 70°C. Coating thickness of 8–12 μm was found optimal for die surface applications. The implemented technology at Fergana Mechanics Plant reduced die manufacturing costs by 7–10% and extended die service life by 6–8%, generating an annual economic benefit of 27,637,500 UZS.

KEYWORDS

Die wear resistance, galvanic cobalt coating, stamping dies, surface treatment, wear mechanisms, mathematical modeling

Introduction

The quality and durability of stamping dies are of paramount importance in the machine-building and automotive manufacturing industries. Die wear directly influences the dimensional accuracy and surface quality of stamped parts, making the enhancement of die wear resistance a critical engineering challenge. In sheet metal forming operations, dies are subjected to intense tribological conditions—high contact stresses, friction, abrasive particles, and thermal loads—that progressively degrade tool geometry and surface integrity.

Globally, extensive research has addressed die wear improvement. Kulka and Keddam (Mechanical Engineering Research Institute, UK; Institute for Machine Tools, Germany) developed low-temperature thermochemical powder treatment in sealed containers, achieving surface microhardness up to 30 GPa. Researchers from Dalian Jiaotong University (China), Fei Xie and Haopeng Yang, developed in-situ boride paste treatment reaching surface hardness of 24 GPa. Russian scientists from Bauman Moscow State Technical University developed diffusion-heterogeneous saturation methods, improving corrosion and heat resistance by 6–8%. Despite these advances, resource-efficient galvanic cobalt coating technologies using local raw materials for stamping die applications remain insufficiently studied.

Within Uzbekistan's national development framework (New Development Strategy 2022–2026), improving the efficiency of manufacturing processes and reducing energy and material consumption are priority objectives. This study aims to address these objectives by developing and validating a galvanic cobalt coating technology to improve die wear resistance and service life in automotive part stamping.

Research Objectives:

(1) Develop a technology to improve die surface layer wear resistance through cobalt coating;
(2) Establish a mathematical model relating cobalt content to wear resistance optimization;
(3) Determine mechanical property changes in cobalt-coated dies;
(4) Evaluate the effect of coating parameters on surface quality and dimensional accuracy.

Research Object:

The study object was a drawing die (stamp no. 96547375.03.00) manufactured from SKD 11 steel, used for forming the front hood attachment component of Chevrolet Lacetti automobiles at Fergana Mechanics Plant.

2. MATERIALS AND METHODS

2.1 Die Material and Surface Preparation

Stamping dies were fabricated from SKD 11 (Japanese standard), a high-carbon, high-chromium cold-work tool steel equivalent to D2 steel. Prior to coating, die surfaces underwent a standardized mechanical preparation sequence: rough milling, semi-finish grinding, heat treatment (vacuum quenching), and diamond burnishing to achieve surface roughness $Ra \leq 1.25$ μm. This preparation ensured adequate adhesion of the subsequent galvanic coating.

2.2 Galvanic Cobalt Coating Process

A sulfate electrolyte system was used for galvanic cobalt-alloy deposition. The electrolyte was prepared using cobalt sulfate, boric acid, and potassium chloride dissolved in distilled water. A custom cathode oscillation device was developed to reduce diffusion limitations during plating. The stepping electric drive enabled cathode oscillation at approximately 25 movements per minute, preventing gas bubble accumulation and ensuring uniform coating distribution.

Key process variables investigated included: electrolyte temperature ($T = 40–70$°C), cathode current density ($Dk = 40–80$ A/dm^2), and deposition time (11–15 min). Two electrolyte formulations were tested: sulfate-fluoride (SF) and fluoride-chlorosilicate (FCS). The coating thickness target range was 8–12 μm for die surface applications.

2.3 Characterization Methods

Cobalt content in coatings was determined by spectrophotometric analysis at 515 nm wavelength using a KFK-3-01 photometer with 20 mm pathlength cuvettes, following dissolution in hot nitric acid. Calibration curves were constructed from three reference standard cobalt solutions. Coating microhardness was measured using a PMT-3 microhardness tester with a tetrahedral diamond Vickers indenter (apex angle 136°) under loads of 0.1–1 N applied perpendicular to the coating surface. Subsrate influence was eliminated by maintaining coating thickness ≥ 8 μm.

Wear resistance was evaluated in simulated dry friction conditions using a standard-load tribometer at 2 N contact force against a 1 mm diameter steel pin. Surface roughness was measured with a profilograph-profilometer equipped with digital recording (Ra criterion). Internal stresses in coatings were determined by the flexible cathode deflection method. Corrosion resistance was assessed through climate chamber testing at 95–98% relative humidity and 40°C.

2.4 Mathematical Modeling and Optimization

A full factorial experimental design was employed to develop regression models linking process parameters (temperature X_1, current density X_2, time X_3) to output responses: coating hardness (y, GPa) and adhesion strength (z, MPa). Models were analyzed in canonical form to determine optimal parameter combinations by locating stationary points. The adequacy of models was verified at a 5% significance level.

3. RESULTS

3.1 Comparative Analysis of Surface Treatment Methods

Four surface treatment methods were evaluated against target specifications (HB $\geq$ 950, Ra $\leq$ 1.25 μm, $\sigma_0 \geq 1000$ MPa): nitriding, cementation, chrome plating, and cobalt coating. A weighted applicability index was calculated for each method using importance coefficients (k = 1.0 for hardness and strength; k = 0.5 for surface finish).

Chrome plating achieved the highest hardness (HB = 1100) and strength ($\sigma_0 = 1000$ MPa) and met Ra requirements, yielding an applicability index of x = 0.97. Cobalt coating achieved HB = 950, Ra = 1.25 μm, $\sigma_0 = 925$ MPa, with x = 0.91. Nitriding achieved x = 0.63 and cementation x = 0.55. While chrome plating showed slightly superior properties, its use involves hexavalent chromium compounds with significant environmental concerns. Cobalt coating was selected as the preferred technology due to its comparable performance, lower environmental impact, and economic advantages.

3.2 Regression Models for Coating Properties

Second-order regression models were established for coating hardness (y, GPa) and adhesion strength (z, MPa) as functions of coded process variables:

$$y = 13.316 + 1.1969x_1 + 0.07813x_2 + 0.091x_3 + 0.1594x_1x_2$$

$$z = 72.125 + 15.5x_1 + 1.625x_1x_2$$

Canonical analysis revealed that the hardness response surface is a circular paraboloid with minimum at the stationary point ($x_1S = 7.51$, $x_2S = 0.49$, $x_3S = 0$), while the adhesion surface is also circular paraboloid with maximum at (xZ1S = 9.54, xZ2S = 0). Optimal process conditions—maximizing hardness while maintaining adequate adhesion—were found in the intersection zone of the two paraboloids. Computed optimal values were hardness ys = 22.93 GPa and adhesion zs = 75.745 MPa. Model validation confirmed good agreement between predicted and experimental values. At T = 450°C, Dk = 40 A/dm², t = 13 min, the model predicted hardness of 12.53 GPa and adhesion of 93.6 MPa, compared to experimental values of 12.4 GPa and 95 MPa respectively (deviation < 2%).

3.3 Effect of Electrolyte Temperature on Coating Properties

Electrolyte temperature was identified as the dominant factor affecting coating microhardness and wear resistance. The relationship between hardness H (MPa) and key process parameters was expressed as:

$$H = 1601.60 - 5.51T^2 + 486.8T + 34.257Dk - 5.625Dk - 30.28T + 1470$$

Increasing temperature from 45°C to 70°C at constant current density caused an approximately 1.5-fold reduction in hardness across all current density values studied. Coatings obtained at 55°C and Dk = 70 A/dm² in the 40–70°C temperature range exhibited the highest wear resistance. Coatings obtained at 60–70°C showed 3.5 times lower wear resistance compared to those deposited at 45–60°C under the same current density conditions.

3.4 Wear Resistance and Tribological Properties

An analytical relationship for coating wear (J, μm) as a function of temperature and current density was established:

$$J = 137.75 - 0.0755T^2 + 7.099T - 3.305T - 0.000935T \cdot Dk - 10.520 - 0.000564Dk^2$$

In dry friction testing, cobalt-coated specimens showed 25–30% higher wear resistance compared to uncoated controls. The contribution of individual properties to wear resistance was quantified:

$$J = 1.37 - 0.105H^* - 0.0456\sigma$$

indicating that microhardness (H*) has a dominant effect on wear amount. The friction coefficient between cobalt-coated steel and cast iron was measured at approximately 35% higher than the cast iron-cast iron pair. Friction run-in period lasted 120–150 minutes after which a stable friction moment was established.

4. DISCUSSION

4.1 Wear Mechanisms in Stamping Operations

Analysis of profilogram data from SKD 11 dies processing SPCC (low-carbon steel), AMG-6 (aluminum alloy), and high-carbon steels revealed distinct wear patterns corresponding to material type. In low-carbon steel stamping, combined adhesive and abrasive wear dominated on die working lateral surfaces. Aluminum alloy forming produced strong adhesive buildup and material transfer due to the high physicochemical activity of aluminum-based alloys. High-carbon steel stamping (thickness 4–8 mm) produced predominantly abrasive wear with 1–3 μm deep scratches on lateral surfaces after 50,000 strokes.

The die working clearance between punch and die matrix critically determines wear mode: insufficient clearance creates additional lateral compression stresses accelerating side-surface wear, while excessive clearance increases shear forces and material slip, also promoting wear. These findings align with Romanovsky's classical crack-formation model: $z_{1,2} = t - h \cdot \tan(\varphi)$, where t is workpiece thickness, h is punch penetration depth, and φ is the material-dependent angle.

4.2 Cobalt Coating Structure and Hardness Mechanisms

The hardness variation with temperature reflects structural changes during cobalt deposition. At lower electrolyte temperatures (40–55°C), a hexagonal close-packed (HCP) cobalt structure predominates with finer grain size, producing higher hardness. Temperature increase promotes formation of face-centered cubic (FCC) cobalt with coarser crystallization, reducing hardness. The cubic modification, while softer, exhibits better ductility and is less prone to brittle fracture under dynamic loading conditions typical of stamping operations.

Internal stresses in cobalt coatings were found to be tensile in both sulfate-fluoride and fluoride-chlorosilicate electrolytes, reaching maximum values at 55°C (SF electrolyte) and 60°C (FCS electrolyte). Increasing temperature reduced internal stress magnitude, though this was accompanied by decreasing hardness. For die components operating under variable loads, coatings with minimum internal stress values were recommended, achievable at 40–45°C or 65–70°C with intermediate current densities.

4.3 Optimal Process Parameters and Practical Application

Based on canonical surface analysis, the optimal cobalt coating regime for die applications requires matching process parameters to specific service conditions. Dies operating at high sliding speed but moderate load require high coating hardness (reduced adhesion), achievable at substrate temperature ~38°C. Dies operating under heavy load at low speed require maximum adhesion to prevent coating delamination, achieved at 46–48°C substrate temperature. This process variability enables application across a wide range of stamping conditions.

The sulfate-fluoride electrolyte was preferred over fluoride-chlorosilicate for production implementation due to easier optimization, better surface finish quality, and lower post-coating machining requirements. Diamond burnishing of cobalt-coated surfaces further improved wear resistance through surface plastic deformation, achieving superior performance compared to ground surfaces alone.

4.4 Economic Analysis and Industrial Implementation

Economic analysis compared the cost of manufacturing new dies versus refurbishment through cobalt coating. New die production cost (SKD 11 blank + CNC machining + vacuum heat treatment + additional work) was calculated at 62,960,000 UZS per die (producing 100,000 parts). Cobalt coating refurbishment cost totaled 7,381,125 UZS (producing 25,000 additional parts), yielding a unit part cost of 295 UZS versus 630 UZS for new-die production—a saving of 335 UZS per part.

At Fergana Mechanics Plant's production rate of 250 Lacetti parts per day (82,500 parts/year), the annual economic benefit totals 27,637,500 UZS. Implementation also reduced cobalt material consumption by 7–9% through optimized coating thickness, and reduced new die procurement expenditure by 7–10%, confirming the technology's strong cost-effectiveness.

These results are consistent with global trends in die maintenance technology. The 6–8% improvement in die service life, while modest in percentage terms, translates to significant savings at industrial production scale. The mathematical models developed provide a quantitative framework for extending this approach to other die materials and stamping applications.

5. CONCLUSIONS

1. A galvanic cobalt coating technology was developed and validated for improving the wear resistance and service life of stamping dies made from SKD 11 tool steel, demonstrating 25–30% wear resistance improvement under dry friction testing conditions.
2. Mathematical regression models were established and validated relating electrolyte temperature, current density, and deposition time to coating hardness and adhesion strength. Canonical analysis identified optimal process windows for different die service conditions.
3. Electrolyte temperature was identified as the dominant process variable: coatings deposited at 55°C with $D_k = 60–70$ A/dm² achieved 3.5 times greater wear resistance than coatings deposited at 70°C. An optimal coating thickness of 8–12 μm was established for die surface applications.
4. The wear resistance equation $J = 1.37 – 0.105H^* – 0.0456\sigma$ confirmed that coating microhardness is the primary determinant of wear behavior, providing a predictive tool for die refurbishment planning.
5. Industrial implementation at Fergana Mechanics Plant reduced die manufacturing costs by 7–10%, extended die service life by 6–8%, and generated annual savings of 27,637,500 UZS, confirming both technical and economic viability of the developed technology.
6. The sulfate-fluoride electrolyte system is recommended for production implementation due to superior process control, surface quality, and compatibility with post-coating diamond burnishing to further enhance tribological performance.

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