INFLUENCE OF CHROMIUM COATINGS ON RELIABILITY AND LIFESPAN OF COIN DIES

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Studies focusing on the quality of chrome coatings applied to coin dies have become essential in the realm of numismatic and metalworking industries. This comprehensive analysis of chrome coating quality and its influence on coin die production reveals invaluable insights for the industry. Through meticulous research, factors such as uniformity or thickness of the chrome coating are meticulously examined. A fundamental aspect of these studies revolves around the impact of chrome coating quality on the reliability and operational life of coin dies.

Keywords: chromium coatings, coin dies, coatings technology, chromium coatings structure, lifespan of coin dies

1. Introduction

Since the days of manually producing coins in forges, coining technology has advanced steadily. Today, contemporary coining machines are used, and each coining die can produce between 750 000 and one million pieces of currency. The production of more coins in mints results in higher coining tool consumption; this has a significant negative effect on the economics of the manufacturing process. The use of high-quality tool steel during the manufacturing process, which will provide the necessary properties after the heat treatment process, is a requirement for getting the best lifetime for coining dies. Making instruments justifies using appropriate techniques to increase their wear resistance. The quality of chrome coatings on coin dies is a critical aspect that significantly impacts the reliability, durability, and overall performance of coin minting processes. Coin dies, which are essential tools in the production of coins, undergo various operational stresses and environmental conditions during their service life. This study delves into the multifaceted aspects of the quality of chrome coatings on coin dies, examining

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their adhesion strength, wear resistance, corrosion resistance, impact on coin quality, aging effects, and microstructural properties. By exploring these dimensions, we aim to gain a comprehensive understanding of how the quality of chrome coatings influences the reliability and operational life of coin dies. Through a combination of experimental analyses, empirical studies, and advanced characterization techniques, this research seeks to contribute valuable insights to the field of coin minting. Ultimately, a thorough investigation of the quality of chrome coatings on coin dies will enable the development of optimized coating processes, improved die designs, and enhanced overall coin production quality. The significance of studies on the quality of chrome coatings on coin dies and their impact on reliability and operational life cannot be overstated. These studies provide invaluable insights that influence the entire coin minting process, from die production to coin circulation. In conclusion, studies focusing on the quality of chrome coatings on coin dies and their effects on reliability and operational life have far-reaching implications. They drive improvements in coin quality, minting efficiency, cost-effectiveness, and even environmental sustainability. These studies underpin the foundation of the entire coin minting ecosystem, ensuring that coins remain not only functional but also valuable and cherished artifacts of culture and history.

2. Conditions of coining die operation

Coining is a technological process that causes cold plastic deformation in the substance under compression in the die. A concave or convex relief has been created on the surface of the plates as a result of this distortion.[1] The upper die and bottom die are the two primary components of the coining die, which is a tool for coining metals. Between them, a negative-shaped gap develops. Fig. 1 shows a schematic of a coining tool.

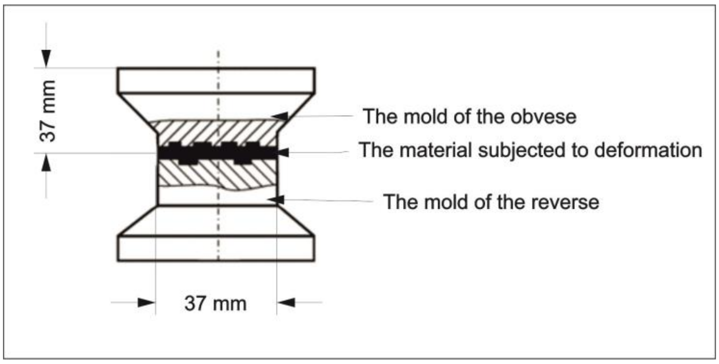

Fig. 1. Scheme for coinage

Coining places material under tension comparable to forging in a closed die. The circular semi-product is compressed inside the tool and takes on the form of the tool's cavity. The material's properties and the piece's relief's structure determine the specific pressure [2]. Greater specific pressure and more intricate relief forms must be used when coining for thinner formed pieces. When silver and nickel coins are struck, the numbers of specific pressures range from 1500 to 1 800 MPa. The method of making coining dies is challenging. First, a relief artistic pattern is made as a plasticine model. After that, a dent acryl cast, and plaster sculpture are created.

Fig. 2. A component of die (the positive mold with which the other molds are made)

On the reduction machine, the relief is shrunk to the size of the future currency. The first die is finally given its form. The initial die is used to create relief on the coining instrument. The process of coining wears out this one, so fresh coining tools must be created [3].

2.1 Coining implement specifications

High standards are set for coining tools in terms of shape precision, surface quality, and structural strength. The tools' design must be modified because they transmit strong forming pressures. The surface treatment of the upper die and lower die's relief is given particular attention. Tool steel that has been hardened and tempered at low temps to a hardness of between 58 and 60 HRC is used to make coining dies [4]. High hardness, adequate toughness, good shape retention, high abrasion wear resistance, pressure strength, suitability for heat treatment, resistance to crack formation during hardening, suitability for some coating methods (depends on tempering temperature), good workability, and good shape ability are the requirements for coining die material.

2.2 Degradation of the material characteristics of coining dies

Material properties, as well as the dependability and lifetime of tools, are significantly influenced by manufacturing and operational degradation [5]. The procedure of steel heat treatment has an impact on production degradation in addition to heat itself [6]. In order to reduce the propensity of the material to form cracks during subsequent heat treatment operations, it is crucial to include annealing, for instance, between forming operations when making coining dies.

[7]. The fatigue failure of the coining die caused by the cyclic action of fluctuating stress is the primary indicator of operational deterioration in coining operations [8]. At a pace of roughly 750 strokes per minute, the coining dies are in use. The coining dies must produce approximately 750 thousand pieces over the course of their lives.

2.3 Choosing the right elements to make coining dies

In order to enhance the functional characteristics of various materials, such as steel, plastics, and glass, hard PVD coatings (nitrides, carbides, carbonitrides, and oxides) are applied. [10]. The substance being processed, and the instrument's operating circumstances influence the selection of the best layer. Because of the high coating temperature, CVD technology cannot be used in situations where PACVD layers can be used. PACVD is used at 500°C and CVD covering at approximately 1000°C [11]. The suitability of the coating substance has a significant impact on the materials chosen for the dies production. A better surface quality of coins and medals can be achieved by applying coatings to the relief of dies, which increase wear resistance [12]. However, plating is currently the most popular technique for extending the lifespan of dies' functional regions. Currently, chroming is one of the most popular riveting processes. The hardness of a chrome layer produced through metallurgy is approximately 300 HV; an electrodeposited chrome covering has a hardness ranging from 700 to 1100 HV. It can withstand temperatures of up to 500°C and has excellent abrasion resistance [13]. That makes it inevitable that a hard coating will develop to treat the surfaces of tools and parts subjected to increased pressure or abrasion wear. Hard chroming is only done to increase the surface toughness; it is not done for aesthetic or anticorrosion reasons. [14]. As a result, it's essential to temper the hardened steel in order to achieve the desired level of hardness, which is 3–4 HRC lower than what the steel manufacturer has specified. Chroming processes are followed by dehydrogenation. Depending on the characteristics and dimensions of the components, it is heated to a temperature of 190–220°C over the course of 2–18 hours. The experiment described in this article examines the quality of the chrome layers on the relief of three unused coining dies that were coated for varying lengths of time. Tool steel Bohler K455 was used to make all three coining dies. Table 1 contains the chemical composition [15]. Coining blades were heated up in accordance with the manufacturer's instructions. According to the instructions of the tool maker, the reliefs of coining dies were chrome-plated for the experiment. Experimental coining dies identification:

- 25 minutes for chroming the coining die R1.
- Coining die R2 took 12 minutes to chrome.
- Coining die R3: coating duration is 15 minutes.
- Coining die R4: coating duration is 10 minutes.

Table 1

Chemical composition of tool steel

C	Si	Mn	Cr	V	W
0.63%	0.60%	0.30%	1.10%	0.18%	2%

3. Measuring the grade of the chrome layer on coining dies.

Experimental observations

An optical microscope was used to perform a microscopic study of the Cr layers on the coining dies, and software for image analysis was used to determine the thickness of the layers. On a longitudinal portion of the coining dies, the thickness and quality of the layering were assessed. By using 2% Nital, the microstructure was incised. The chrome layer is deposited all over the scrutinized relief, flaking off and cracking irregularly on the coining die R1 (Fig. 3A-D). There are places in the layer where globular non-metal immixtures are visible in the relief's surface structure, which led to the development of cracks under the adverse structural stress shown in Fig. 3. On the coining die R1, the Cr layer's maximum thickness was 10.9 microns and lowest thickness was 10.3 microns. Fig. 3E, F illustrates the procedure for measuring thickness using image analysis tools.

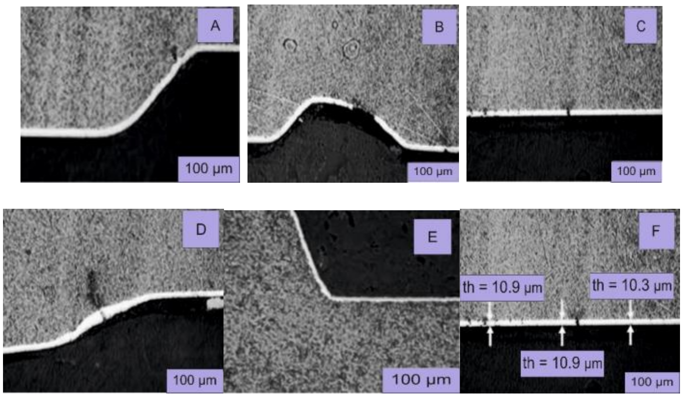

Fig. 3. R1- coining die - condition of Cr layer on the relief A-D and lines of measurement for thickness E, F

After 12 minutes of coating, the Cr layer on the coining die R2 is discontinuous, occasionally not deposited, and extremely thin. (Fig. 5A–D). The layer had the highest thickness of 2.53 microns and a minimum thickness of 1.20 microns.

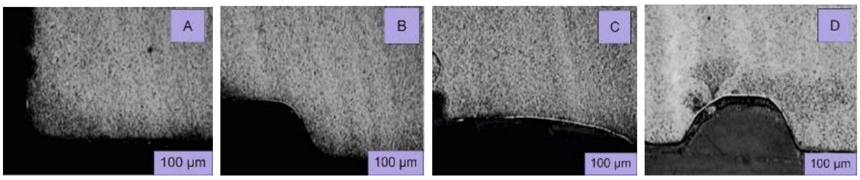

Fig. 4. R2- coining die - condition of Cr layer on the relief

The order of Fig. 5A–F outlines the circumstances surrounding the etching on coining die R3 in question. The layer is continuous and looks like a thin, cracked layer; it was not at all deposited on one side of the coining die. The layer's quality differs across the relief; it is thicker and cracked in some spots.

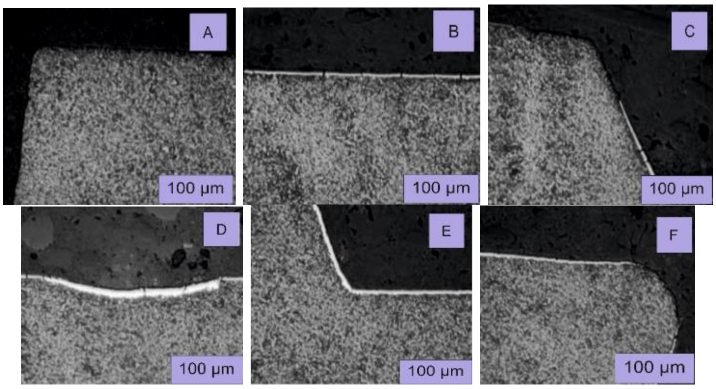

Fig. 5A-F. Layer of chromium on the coining die R3

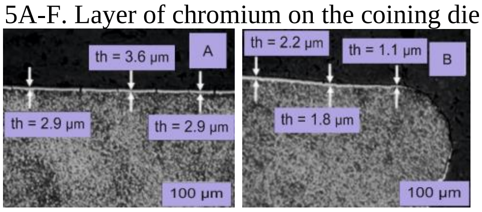

Fig. 6. Coining die R3 - Points of measurement for thickness

Using the NIS Elements software, layer thickness on the coining die R3 was measured, as shown in Figs. 6A and 6B. The layer had a highest thickness of 3.6 microns and a minimum thickness of 2.9 microns in the middle of the coining die and between 1.1 microns and 2.2 microns on its edges. After microscopic analysis of the chromium layer we noticed that the following defects may appear:

- In Fig. 3B we can observed that we have **porosity**: The presence of pores and small voids in the chrome layer has diminish the quality of coin details and finish. Porosity can result from various factors, such as deposition conditions, the quality of the chrome solution, or improper preparation of the die surfaces.
- In Fig. 5D we can observed that exist **uneven coating**: in this case the

chrome layer was deposited unevenly on the die's surface, leading to inconsistencies in the thickness of the layer and the final appearance of the coins. This can be the result of uneven distribution of electric current during the chrome plating process.

- In Fig. 5B we can observed that we have **fissures**: The chrome layer was develop cracks or fissures due to internal stresses and exposure to high temperatures during the chrome plating process.
- In Fig. 5C we can observed **discoloration and darkening**: Chrome was exhibit discoloration and darkening, affecting the overall appearance of the coins. This can be caused by interactions with impurities in the chrome solution or deposition conditions.
- In Fig. 4D we can see that **deformation** appear**:** The chrome plating process has induce thermal and mechanical stresses that might cause deformations in the dies. These deformations can result in coins with incorrect dimensions or shapes.

The experimental findings of the examined coining dies refer to these values because they might be considered optimal in terms of the declared lifetime. These dies have had an acceptable lifespan withstanding the pressing of approximately 350.000 coins. The coining dies R2 and R3 had low layer thickness measurements, and the quality of the layers in terms of evenness and integrity throughout the inspected relief was subpar. Layer thicknesses ranging from 10,3 microns to 10,9 microns were measured on the coining die R1 coated for 25 minutes, but according to information from the maker of coining dies, thick layers over 10 microns have tendency to flake under load in operation. This phenomenon might also be accelerated early by the Cr layer cracks on coining die R1. The quality of Cr layers is one of the most important variables, even though a few of the aforementioned factors affect the lifespan of coining dies. Experiments' findings indicate that coating duration affects the grade of chrome layers. The precise goal of the experiment was to ascertain how this parameter affected the thickness of the deposited layer and its quality.

To minimize these defects, it's crucial to carefully monitor each step of the chrome plating process, employ high-quality equipment, and adhere to stringent quality control standards.

To ensure the quality and consistency of this coating, it is important to observe certain experimental conditions. In order to avoid the above mentioned defects, it was checked if the general basic conditions were respected. But in order to verify the correctness of the experimental conditions, a new die was made and chrome-plated under ideal conditions.

4. Current chromium plating improvement methods

In improving the chromium plating process of a new coin die R4, the following main aspects have been taken into consideration:

Surface preparation of coin dies before chrome plating

Proper surface preparation is crucial for achieving successful and high-quality chrome plating on coin dies. The condition of the coin die's surface before plating significantly impacts the adhesion, uniformity, and overall quality of the chromium layer. Here are the essential steps involved in the surface preparation of coin dies before chrome plating: cleaning, stripping previous coatings, degreasing, mechanical cleaning, etching, activation, rinsing, drying.

Following these steps diligently ensures that the coin dies' surface is clean, well-prepared, and optimized for receiving the chrome plating. Proper surface preparation maximizes adhesion, minimizes defects, and contributes to the overall quality and longevity of the finished coin dies.

Analyzing the chrome plating solution

Analyzing the chrome plating solution is of paramount importance in ensuring the success of the plating process, maintaining the quality of the plated coatings, and preventing defects. The composition and condition of the plating bath solution directly influence the characteristics of the plated layer and the overall efficiency of the plating operation. To verify the chromium plating solution, a representative sample of the plating solution is collected and subjected to detailed analysis. The pH level of the chromium plating solution plays a crucial role in determining the quality, properties, and appearance of the plated coatings. Drastic pH changes can destabilize the bath and lead to variations in plating quality. Impurities in chrome plating baths can have a significant impact on the quality of the plated coatings and the overall performance of the plating process. These impurities can originate from various sources and can lead to defects, inconsistencies, and compromised properties in the plated layers. The most destructive impurities are metallic impurities. Trace metals such as iron, copper, zinc and nickel can enter the plating solution from a variety of sources including anodes, substrates and equipment. Metal impurities can change the chemical composition of the coating, affecting its properties. The results of the chrome plating solution analysis are presented in the following table:

Table 2

The results of the chrome plating solution analysis

Parameter	Unit	new value	last value	nominal value
Density	°Bé	24,0	-	
pH Value		4,5	-	3,9-4,6
nickel	g/l	90	-	70-85
chloride	g/l	14	-	14-20
boric acid	g/l	37	-	37-45
ELPELYT LS-1 Carrier X5	ml/l	14	-	
surface-tension 110 ms	mN/m	64	-	
Copper	mg/l	17	-	
zinc	mg/l	28	-	
iron	mg/l	21	-	
chromium	mg/l	2	-	

Trivalent chromium must be below 8 g/l, conductivity above 300 mS/cm, iron maximum 8 g/l, surface tension between 30-40 mN/m, nickel is an impurity for these baths, and the value is very high. The influence of impurities on the conductivity of the chromium bath is shown below:

- Iron - 12.4 mS/cm per gram;
- Copper - 6.0 mS/cm per gram;
- Chrome III oxide - 9.7 mS/cm per gram (as Cr_2O_3);
- Sodium - 5.8 mS/cm per gram;
- **Nickel - 11.7 mS/cm per gram;**
- Zinc - 8.4 mS/cm per gram.

The effect of foreign metals on the conductivity varies from element to element.
Considering that impurities were found in the chromium plating solution, it was decided to replace the chromium plating solution with a solution complying with the nominal values shown in Table 3. After replacing the chrome plating solution, the R4 die was chrome plated under ideal conditions and then tested in production.

Fig. 7 shows the lifetime of each mould tested and how the R4 mould which was chrome plated under ideal conditions was very durable compared to the others dies.

Fig. 7. Lifespan of chrome plating dies

Thus, we have demonstrated that the improvement method proposed in this research based on the removal of impurities from the chrome plating solution, table 4, helps to protect the dies during the coin pressing process.

Table 3

The chrome plating time and lifespan

Die type	Chrome plating time[min]	Lifespan [pcs]
R1	25	350000
R2	12	390000
R3	15	450000
R4	10	750000

The layers on the coining die R4, Fig.. 8A-B which produced 750 000 coins in its lifespan, were assessed. After discarding from the coining procedure, the thickness of layers ranging in thickness from 8 to 10 microns was measured on the coining die. The die was stopped from the production process because during the pressing of the coins between the coin and the die impurities were trapped which could not be removed manually from the die.

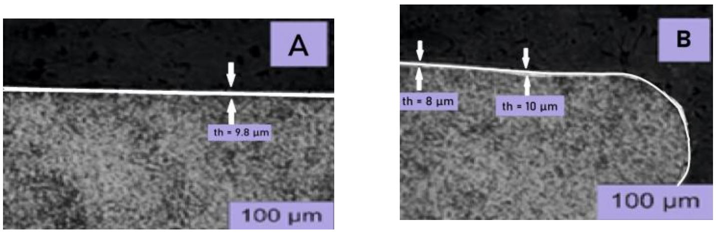

Fig 8. Coining die R4 - Points of measurement for thickness

The R4 die was de-chromed and chrome plated again and production continued with it.

Fig. 8A-B shows a layer thickness with small variations between 8 and 10 microns. It can be seen in Fig. 8A-B that there were no defects in the R4 mould. the chrome layer on the mould was hard, homogeneous and compact. Given the experience with R1 mould which had a layer thickness of more than 10 microns, peeling of the chrome layer occurred.

Table 4

The die lifespan and the thickness of the chromium layer

Die type	Average chromium plating thickness[µm]	Lifespan [pcs]
R1	10.6	350000
R2	1.9	390000
R3	2.4	450000
R4	9	750000

We can conclude that the thickness range between 8 and 10 microns may be ideal as shown in Fig. 9.

Excessive chromium layer thickness on a coin die can have significant negative consequences on the coin production process. This can lead to peeling of the chromium layer, resulting in its separation or detachment from the die surface. At the same time, too thick a chromium layer can fill in the fine details of the die, which are essential to create the precise details of the coins. This overfilling can result in coins with distorted or incomplete detail.

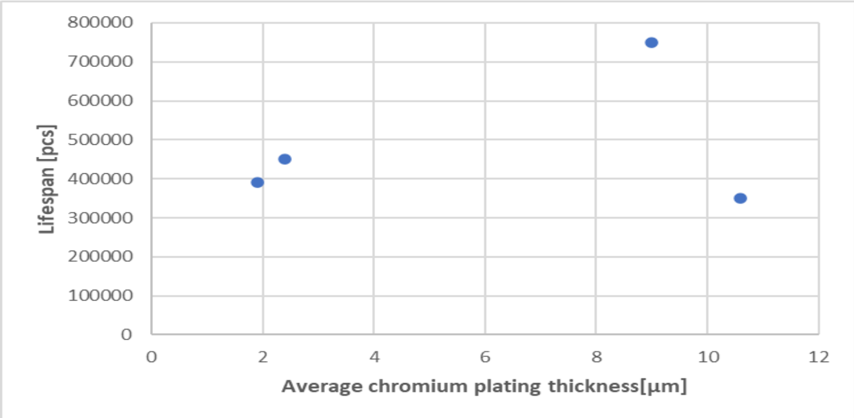

Fig. 9. The die lifespan depending on the thickness of the chromium layer

Too thin chrome layer thickness on a coin die can also cause significant problems in the coin production process. problems related to a thin chrome layer thickness could be decreased corrosion resistance, rapid die wear and reduced durability.

5. Conclusions

It can be confirmed that preparing a new solution for chrome plating baths of coin dies is critical for achieving consistent, high-quality plated coatings. It ensures accurate composition, controlled parameters, and optimal performance, ultimately leading to successful plating processes and desirable coating properties on the coin dies. It can be said that the quality of the chromium (Cr) layer on coin dies plays a critical role in determining the die life and the quality of the coin products. This influence becomes particularly evident when considering varying durations of the chromium plating process. The findings highlight the delicate balance that must be struck to achieve optimal results in both die performance and coin product appearance. The Cr layer's impact on die life is evident through factors such as its thickness, uniformity, and adhesion. A well-deposited Cr layer with the right thickness and uniform distribution enhances the die's wear resistance, extending its operational life. Adequate adhesion ensures that the layer remains intact, further contributing to longevity. Regarding coin product quality, the Cr layer serves as a crucial medium for design transfer, surface finish, durability, and overall consistency. Optimal Cr layer quality translates into well-defined and uniform coin designs, appealing surface finishes, and coins that retain their appearance and structural integrity over time. However, the duration of the chromium plating process introduces complexities. Short plating durations may lead to insufficient layer thickness and inadequate protection, impacting both die life and coin quality. Conversely, excessive plating times can result in overly thick, brittle layers that compromise adhesion and introduce defects. In essence, achieving the right balance in Cr layer quality, especially under varying plating durations, demands precision. An optimal Cr layer thickness, uniformity, and adhesion are prerequisites for extended die life and high-quality coin products. Careful consideration of the plating process duration is essential to prevent under- or over-plating, which could compromise these attributes. From this experiment it was found that if the chromium layer is too thin (R2 die with a layer thickness between 1.2 microns and 2.53 microns, and R3 die with a layer thickness between 1.1 microns and 3.6 microns), it does not provide sufficient protection against wear and corrosion, and the die could deteriorate faster. On the other hand, too thick a chromium layer (R1 die with a layer thickness of 10.3 microns to 10.9 microns) could affect the fine details of the coin design, lead to peeling and cracking of the chromium layer, or cause difficulties in the production process. Therefore, it can be considered that the optimal thickness of the chromium layer on the coin dies should ideally be kept within the values measured on the R4 die (between 8 microns and 10 microns), since this die has a much longer lifespan than the other dies. In addition, we can say that this scientific work contributes both to improving the overall quality of the materials used in moulds and to improving the way they are heat treated and processed. The use of these advanced manufacturing techniques and high-quality materials can contribute to prolonging the life of the dies and to obtaining higher quality coins. Thus, correlating the thickness of the chromium layer with the lifetime of the coin dies is essential to achieve durable, aesthetic and high-quality coins that will stand the test of time and frequent use. As the coin minting industry continues to evolve, it is imperative to prioritize the research and application of effective chromium plating techniques. This involves meticulous process control, quality assurance, and continuous refinement of plating parameters. By ensuring that the Cr layer meets the desired standards regardless of plating duration, manufacturers can achieve durable dies, consistent coin product quality, and contribute to the longevity and value of coins in circulation and in collectors' hands.

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