PLATING SURFACE CORRUGATION

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I am convinced that plating surface corrugation on copper plated zinc cents, often observed as ridges and valleys, is caused by issues in the plating process. (See photo below).

> **►Since plating ripples also appear on unstruck planchets, we know that the ripples appear prior to striking.**
>
> **►The irregular shape of individual ripples indicates that they are not planchet striations, which are expected to present a more linear morphology.**

I find the possible causes of surface corrugation of copper plating varied and complex.

Since copper is a Nanocrystalline (NC) metal, it has a face-centered cubic crystal structure that is prone to exhibit plastic deformation. The plating process itself leaves the copper plating with residual stress. An improper balancing of the elements of the plating process can amplify these pre-existing internal plating stresses. These stresses may be due to lattice mismatch, grain boundary interactions, and/or the incorporation of impurities, leading to a stress gradient across the film thickness. Ready To Strike (RTS) planchets are provided to the US Mint by a supplier where a barrel plating process is used. The variable elements of the plating process include: power supply (voltage), temperature, plating time, solution concentration, barrel drum rotation speed, and pH level.

These stress gradients can significantly affect the mechanical properties of the copper film, including its adhesion to the substrate,

susceptibility to cracking, splitting, rippling, bulging, blistering, and bubbling, and potential for interface delamination.

{While "Delamination" is frequently used in references discussing electroplating, it is not being used in the numismatic sense of "separation of an alloy along internal planes of weakness." It is used in reference to the separation of the copper plated film from the substrate. A more appropriate descriptive for our purposes would be "peeling." (Unfortunately, some TPGs have adopted the non-numismatic usage of the word).}

I think what is happening to produce the ridges and valleys in the copper plating is that: As the crystalline lattice structure of the plating reorients to release stress, alignment occurs and ripples form in roughly parallel rows. The reduced stress level of the ripples has actually been verified in experiments by measurements.

This hypothesis is born out at the atomic level, where it has been found that thin Copper films are one of the nanocrystalline (NC) types of metals that have a preferred grain orientation. Since Copper is a face-centered-cubic metal that often grows with surface orientation, it might be expected that individual grains and GBs (Grain Boundaries) would coalesce to form films with smooth surfaces. However, GBs in metals such as Cu are composed of stacking faults (SFs) whose energies have a directional dependence that could induce grain rotation and concomitant surface roughening.

A research paper (Nanocrystalline copper films are never flat) discusses the corrugation found as Grain Boundaries (GB), emerging at the surface, and forming ridges and valleys on thin copper films.

"The presence of grain boundaries and their emergence at the film surface create valleys composed of dissociated edge dislocations and ridges where partial dislocations have recombined. Geometric analysis and simulations indicated that valleys and ridges were created by an out-of-plane grain rotation driven by reduction of grain boundary energy."

The paper reports the employment of the use of scanning tunneling microscopy (STM) to map the local three-dimensional topography of GB intersections at surfaces with picometer (a picometer[pm] is equal to 1×10^{-12} meters, or one trillionth of a meter) precision.

The paper asserts that Copper has a relatively low Stacking Fault (SF), so a lattice dislocation normally dissociates into two Shockley partials separated by a SF. This results in the GBs at valley and ridge locations showing different corrugation amplitudes which would account for the irregular visual appearance of the ripples on the surface of copper plated zinc cents.

►For those interested, Images and advanced mathematical formulas for a Burgers Vector and Shockley Partials are provided in the referenced paper. For a more detailed discussion of Shockley Partials, Stacking Faults, Frank Partials Dislocations and Burgers Vectors, see: https://www.sciencedirect.com/topics/engineering/shockley-partial#:

In the barrel plating process, the individual pieces establish a bipolar contact with one another. This may produce variations in current density, which - along with barrel spinning speed and solution composition, become primary influencers in affecting surface roughness.

So, the overall specific mechanisms at work appear to be that the surface corrugation in thin copper films, often observed as ridges and valleys, arises from factors like anisotropic strain relaxation, thermal contraction of the substrate, and grain boundary defects, impacting the film's properties. During the growth of thin films, the interaction between the film and the substrate can lead to anisotropic strain relaxation, where the film contracts or expands unevenly. This can result in surface corrugations as the film tries to relieve the stress.

The best (unverified) explanation I can offer for the rippling being oriented in the same direction on both sides of the planchet/coin is that the copper plating performs as a single dynamic layer of copper surrounding both sides of the planchet/coin and distorts as a single unit rather than two separate, independent halves on either side of the coin.

I find it interesting that corrugation or rippling issues are also the cause for serious concern in numerous other areas: from sewing stretch fabric, to mechanical properties of cell walls, to the design of submarine hulls. Complicated mathematical formulas have been devised for working in these areas, including Föppl–von Kármán equations, a set of nonlinear partial differential equations. Extensive explorations have been made into the geometry and physics of wrinkling.

SUMMARY

Since copper is a Nanocrystalline (NC) metal, it has a face-centered cubic crystal structure that is prone to exhibit plastic deformation. During plating, stress gradients are formed within the plating and may be amplified by various elements of the plating process. As the crystalline lattice structure of the plating reorients to release the stress, ridges and valleys are created by the grains rotating out of plane.

References:

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