WHY DOES PLATING CRACK and SPLIT?

A tentative theory explaining the cause of circumferential plating cracks and split plating.

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As I was discussing my thoughts with an acquaintance who is both a Numismatist and a Metallurgist, he said: "When we do failure analysis, we run a series of tests, like put it on the SEM, confocal, run chemistry, hardness, etc. Then we analyze the results and formulate a theory based on the data. I just think without data…it is more like…throwing spitballs." Since my theory is extrapolated from the work of others and not the result of testing, I may be throwing spitballs!

According to Error-Ref, plating that peels up or cracks before or after the strike is comparatively rare.[1] I have certainly found that to be the case as I have researched the subject, finding a paucity of examples. (Two examples of a Circumferential Plating Crack follow).

My tentative theory is that these features appear, as the result of stress in the copper plating, along the Yield Point (that area where

elastic deformation of the copper plating becomes plastic deformation).

Explanation of stress:
Elastic Region: Initially, as stress is applied, the material deforms elastically, meaning it will return to its original shape once the stress is removed. This region is characterized by a linear relationship between stress and strain (Hooke's Law).[2]

Yield Point: When the stress reaches the yield point, the material transitions from elastic to plastic deformation. This point marks the limit of elastic behavior and the start of permanent deformation. Since these examples of circumferential plating cracks are approximately 1 mm from the design rim, I think the implication is that a distance from the rim of approximately 1 mm defines the area of the Yield Point for our purposes.

Plastic Region: In this region, dislocation movement is the primary mechanism for deformation. As the applied stress exceeds the yield strength, dislocations begin to slide past each other, allowing the material to deform permanently.

In summary, dislocation movement in copper begins just after the yield point in the plastic region of the stress-strain curve.

There are at least 3 primary sources of stress in the copper plating on a cent:

- **The inherent stress within thin films of copper plating**
- **The corners (areas where the field meets a device) of the design**
- **The stretching of the copper plating produced by the strike itself**

Inherent Stress:

The electroplating of a cent is with 8µ[3] thickness of copper. Planchets used by the US Mint for the cent are obtained from Jarden Zinc where they use a barrel plating process (see photo below). (Jarden Zinc is now rebranded as ARTAZN LLC.) Plating is applied after the blanks pass through the upsetting mill.[4]

Barrel Plating Line, Jarden Zinc

http://jardenzinc-com.web01.adigitalhost.com/Plant-tour-jarden-zinc.aspx

While thinner foils of copper plating have a smaller fracture strain and a higher tensile strength than thicker foils[5] (meaning they are less likely to fail), they are nevertheless susceptible to failure under the

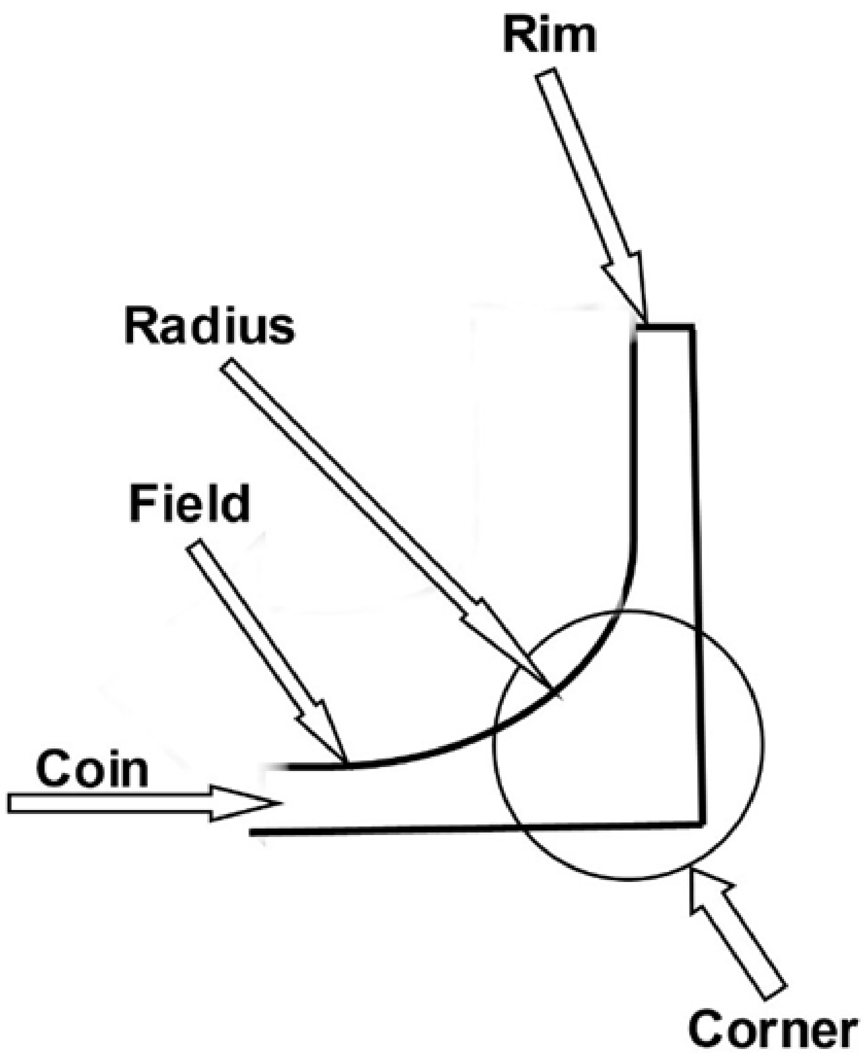
right combination of conditions, with inherent stress a contributing factor. "…thinner Cu films show larger values of residual stress…"[6]

This stress arises from factors like lattice mismatch between the deposited copper and the substrate material, grain boundaries within the copper layer, and the rapid deposition process itself, which can trap internal strains. Variations in bath chemistry and cleaning of blanks prior to entering the process may influence the results, resulting in higher stress levels.

Corners:

Metallurgically, a corner[7] (where the field meets a device) needs to have optimized radius. If the radius is too large, wrinkling (rippling) of the plating will result (see photo page 17). If the radius is too low (closer to a right angle), it produces a source of stress which causes the plating to split. (See diagram below for definitions). Cracks are more likely to initiate and propagate at corner locations.[8]

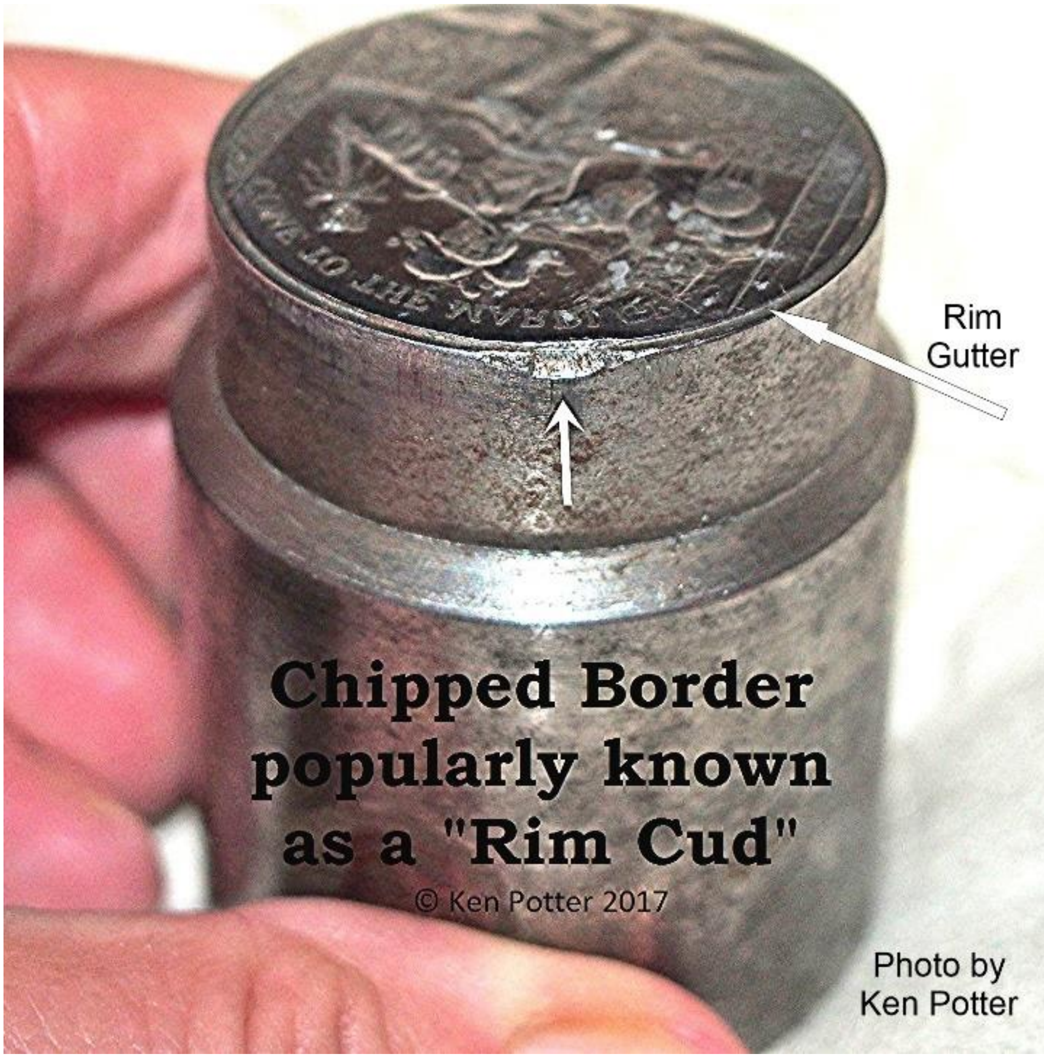
In the overall field of mechanical design, achieving an optimal corner radius is critical for minimizing stress, among other benefits.[9] For example, in the automotive and plumbing industries a basic tenant is: "One of the most important design features that can affect the electroplating quality is that of radii and corners. As we discussed earlier sharp edges and corners should be avoided for plastic parts that are going to be electroplated because of the buildup of metal on these surfaces."[10]



Since the plating is only 8 µ thick, unevenly distributed stress is magnified in surface abnormalities including splits and cracks. Plating cracks may show randomly across the surface, or be guided by a predefined stress pattern, such as that provided by the suboptimal radius (too low) of a design rim.

The radius of the design at the rim/field junction is formed at the boundary between the Die Face and the Rim Gutter. (A Rim Gutter is shown on the image of a die in the image below). A sharp edge at that

boundary will produce a radius that is too low, and an excessively rounded edge will produce a radius that is too large.



Copper is highly anisotropic (having a physical property that has a different value when measured in different directions). We know that the stress state close to a geometrical variation, such as a sharp corner, is inherently multiaxial[11] and that stress diminishes in intensity further away from the corner.

In addition to the proximity to a corner producing stress, stress in copper plating in the field near the rim is produced as the strike raises the design rim thus stretching and stressing the copper plating further

and also from the outward metal flow from the center of the die. Notice that most examples of circumferential cracks show a rather strong internal design rim margin.

As the stress produced enters the plating in the field inside the design rim, the copper plating first experiences elastic deformation, meaning it will return to its original shape once the stress is removed. This region is characterized by a linear relationship between stress and strain (Hooke's Law). When the stress reaches the yield point, the material transitions from elastic to plastic deformation. This point marks the limit of elastic behavior and the start of permanent deformation. At this point a crack develops and follows the curve of the design rim. The Yield Point serves as a kind of Road Map for the crack to follow.

These observations lead us to the question: "If a suboptimal radius at the rim/field junction leads to a circumferential plating crack, why are not all coins minted from that die stage showing such a crack?" I think we must look at irregularities in the plating for the characteristics that will initiate cracking, including:

- **Plating thickness variations**
    - **Current Density (see explanation below)**
    - **Bath chemistry: Impurities or incorrect concentrations of chemicals in the plating bath can significantly affect the deposition process, leading to uneven plating.**
    - **Agitation: Insufficient agitation can create "dead zones" in the plating bath where the solution is not properly mixed, causing uneven deposition.**

- **Workpiece geometry: Complex shapes can create areas with varying current densities due to the way the electric field distributes across the surface.**
- **Temperature variations: Fluctuations in bath temperature can affect the deposition rate and uniformity.**
- **Surface preparation: Poor cleaning or surface irregularities can lead to uneven plating.**

- **Hydrogen embrittlement**

Plating thickness variations:

It may seem counterintuitive, but generally, a thinner plating of copper is more resistant to failure than a thicker plating[12] so an area of thicker plating may also be an influential factor in the appearance of cracks or splits. The thinner plating has a higher yield strength, frequently around 200 to 300 MPa (MPa = mega Pascals, a measurement of units of pressure). (The tensile strength of an 8µ thick copper foil is typically around ≥294 MPa.)

"The tensile strength and fracture mode changed with thickness of copper foil obtained from an acid copper sulfate bath under a same electrodeposition condition. The tensile strength decreased with increasing foil thickness due to an increase in average grain size of the foil. The tensile fracture mode changed from fractures normal to tensile axis to inclined fractures with increasing film thickness. The phenomena have been discussed based on a hardness distribution along the thickness and the local necking and fracture strains."[13]

Since areas of thicker plating would likely be only incrementally thicker, the actual impact is likely to be limited, but may remain influential when combined with other plating irregularities.

Current density:

High current densities can lead to localized deposition, resulting in thicker layers in certain areas and thinner layers in others.

Current density is the measure of the amount of electrical current flowing through a given area in electroplating. It is typically measured in amps per square foot (A/ft^2) or amps per square meter (A/m^2). It is an important factor in electroplating as it determines the rate of deposition for the metal ions into the substrate, resulting in the eventual thickness of the coating. The higher the current density, the more metal ions are deposited in the substrate and the thicker the coating.[14]

Hydrogen embrittlement:

Hydrogen embrittlement in copper barrel plating is a phenomenon where the copper plating process introduces hydrogen atoms into the base metal, causing a loss of ductility and making the material more brittle.

"…slow strain rate hydrogen embrittlement can operate in electrodeposited copper provided that the hydrogen concentration is sufficiently high. Further analyses revealed that the deformation of embrittled copper is achieved by the formation of internal microcracks which coalesce at the point of failure."[15]

There are various other defect types possible during the plating process.[16] Suffice it to say that various combinations of these

difficulties may present in the plating of a cent in sufficient intensity to cause a crack to develop in the plating.

Plating cracks have been misattributed as laminations which might be acceptable in the woodworking arts, but it does not express the numismatic definition of a lamination being a separation in an alloy along horizontal planes of weakness.

I suspect that the different definitions of lamination (delamination) are a major contributing factor to some TPGs attributing a plating peel on a zinc cent as a lamination. This is one such example. Here it is quite clear that a linear plating blister has broken open at its upper end, resulting in a plating peel and not a lamination as would be numismatically defined.

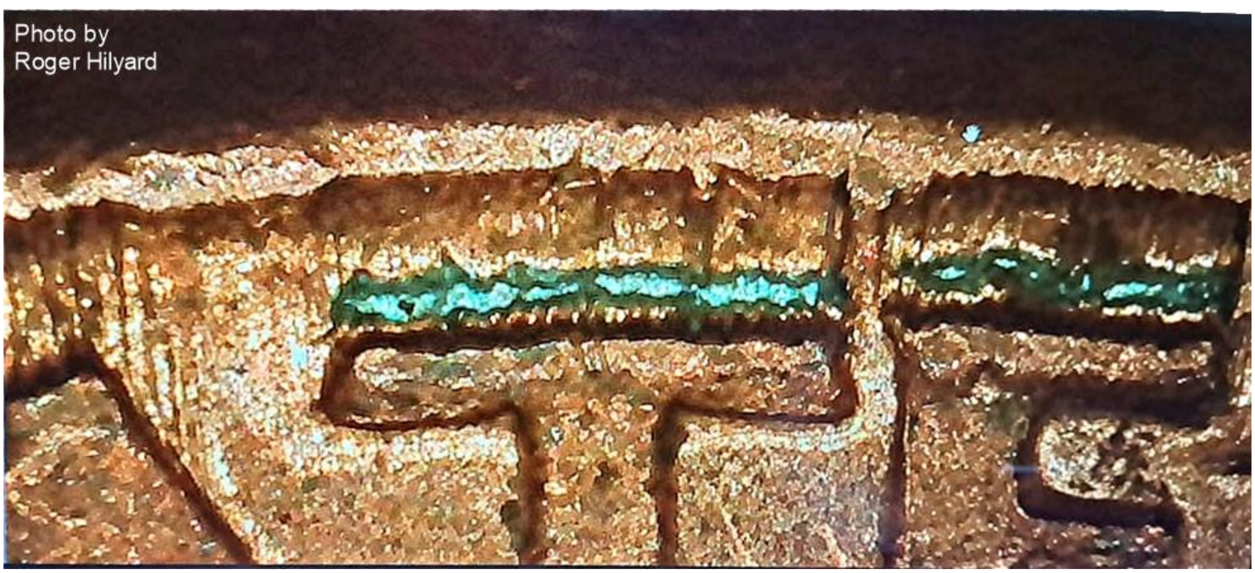
SPLIT PLATING

Whereas plating cracks are most likely initiated by plating irregularities, split plating may be more of an expression of the geometry of the various die devices.

The geometry and sources of stress I have already mentioned in the first part of this paper are all in play as influential for the creation of plating splits. Unlike plating cracks, split plating is relatively common, appearing on peripheral devices as well as devices further from the rim, such as the external edges of the Memorial and the outline of Lincoln's Bust and the Mint Mark. The split usually shows on the side of the device closest to the rim. I think this location is due to metal flow during the strike as the plating is stretched along with that flow towards the outer edge of the coin.

This metal flow towards the rim of the coin happens because of the convex shape of the face of the die. The die is purposefully domed so it may strike coins that are slightly concaved or basin shaped. The reason is that this camber will lower all design relief below that of the rim, thus with all design lower than the rim, it will reduce wear on the design while the coin is in circulation. The rim bears the brunt of all surface wear (until the rim itself is worn down to the level of the design).

The purpose for giving the die face a slight curvature was also to facilitate the movement of metal during the coin striking process. Some examples of split plating even show the flow lines associated with this metal movement. For example, this coin shows the flow lines affecting the morphology of the splitting area.



This coin shows flow lines embedded in the split areas.

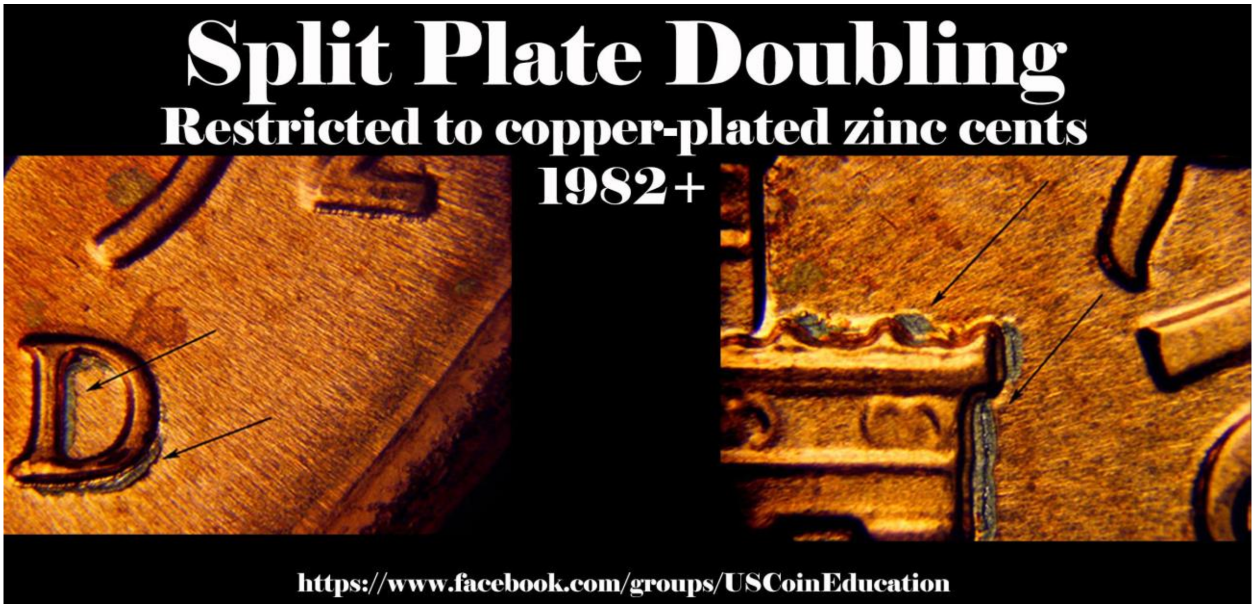
In the following even more dramatic examples of metal flow (photos by Mike Diamond), we gain appreciation for the extent of the flow. The plating has snagged on sharp-edged posts and corners in the corresponding recessed letters of the die face and carried their modified shapes above the letters themselves.[17]


GOD
1994


1999-D

An additional benefit of a slightly curved die face is that it aids in the release of the coin after it is struck and once the die is retracting. If the die face were flat, it would cause the coin to "hang up" in the die, since the pressure of striking would cause the coin to adhere to the upper die.

I think that the suboptimal radius of a device is the primary determinant for the appearance of split plating. In the first part of the paper, I quoted: "Copper is highly anisotropic (having a physical property that has a different value when measured in different directions). We know that the stress state close to a geometrical variation, such as a sharp corner, is inherently multiaxial."[11] I think that these characteristics are responsible for the elastic zone along the rim being further away (approximately 1 mm) from the rim as compared to the elastic zone for a single letter. Notice that the point of initiation of the copper disturbance is typically further away from the rim than it is from a single letter. In other words, a longer uninterrupted linear edge to a device seems to have the effect of extending the elastic zone and yield point further away from the device. Notice the splitting along the edge of the Memorial in the following photo is further away from the edge than that on the mint mark.



These examples of split plating arise primarily from a suboptimal corner where the radius is too low (the corner is closer to a right angle).

When the radius is too high, wrinkling (rippling) of the plating will result (see photo).

The dynamics of copper plating discussed here are, I think, selectively applicable to other expressions of plating issues, such as Plating Blisters, Plating Disturbance Doubling, Peeling Plating, and Subsurface Corrosion.

SUMMARY

Copper plating on a Lincoln Cent develops a CRACK primarily because an issue with the plating process causes irregular inherent plating stress. For a Circumferential Plating Crack, a suboptimal radius of the junction between the die face and rim gutter provides a "road map" for the crack location.

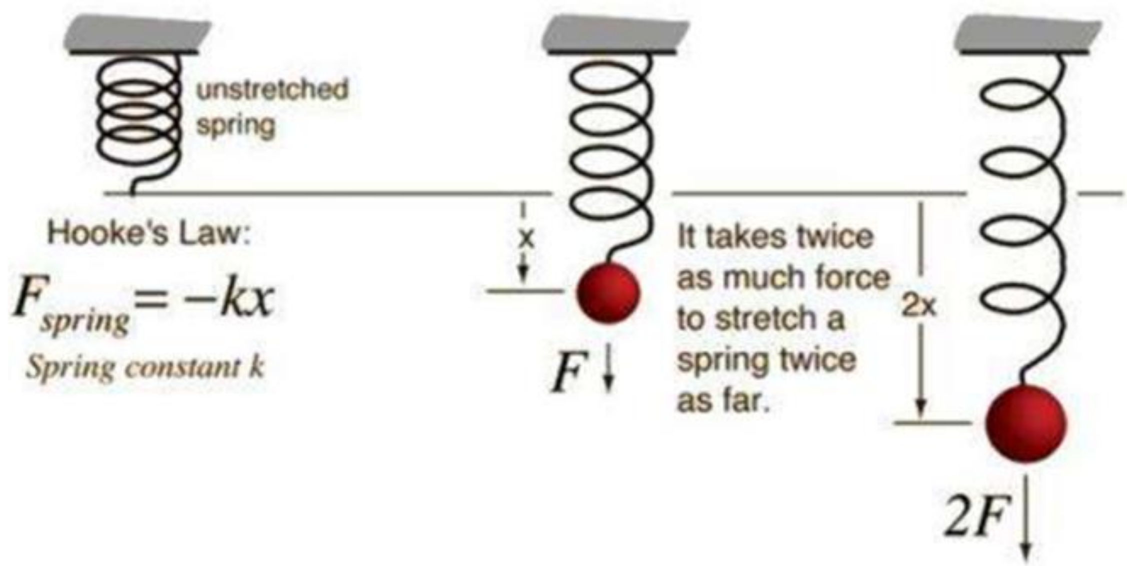
The plating SPLITS primarily because of the stress from a suboptimal radius of the junction between a device and the die face.

FOOTNOTES

It will be evident to anyone knowledgeable in the discipline of metallurgy that I am a complete novice in the field. My hope is that places where I may have misunderstood concepts presented in the papers referenced will be counterbalanced by identifying a convenient resource for use by those more knowledgeable than I.

1.https://www.error-ref.com/cracked-and-peeling-plating/

2. Hooke's law is the first classical example of an explanation of elasticity—which is the property of an object or material which causes it to be restored to its original shape after distortion. This ability to return to a normal shape after experiencing distortion can be referred to as a "restoring force". Understood in terms of Hooke's Law, this restoring force is generally proportional to the amount of "stretch" experienced.



https://phys.org/news/2015-02-law.html#google_vignette

3. ALTERNATIVE METALS STUDY Contract Number: TM-HQ-11-C-0049 FINAL REPORT August 31, 2012 by Concurrent Technologies Corporation, Submitted to: United States Mint, Page 1, Section 1.1

4. The modern minting process and U.S. minting errors and varieties (ANA correspondence course), by James Wiles, Jan 1, 1997, Page 54.

5. "Mechanical Size Effects in Thin Copper Foils: An Experimental Study" - A dissertation submitted to the SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH for the degree of Doctor of Technical Sciences presented by Gerd Simons, Dipl. Masch. -Ing. ETH, Zurich 2004, page 130

6. "Residual Stress and Microstructure of Electroplated Cu Film on Different Barrier Layers", by Alex A. Volinsky, Meike Hauschildt, Joseph B. Vella, N.V. Edwards, Rich Gregory, William W. Gerberich, Motorola Digital DNATM Labs, Process and Materials Characterization Lab, Mesa, AZ, University of Texas, Materials Science Lab for Interconnect and Packaging, Austin, TX, University of Minnesota, Dept. of Chem. Eng. and Materials Science, Minneapolis, MN, Mat. Res. Soc. Symp. Proc. Vol. 695 © 2002 Materials Research Society, Page, L1.11.6.

7. "Singularities in Finite Element Modals: Dealing with the Red Spots" by Henrik Sönnerlind, https://www.comsol.de/blogs/singularities-in-finite-element-models-dealing-with-red-spots

8. "Failure Mechanisms and Optimum Design for Electroplated Copper Through-Silicon Vias (TSV)", Xi Liu, Qiao Chen, Pradeep Dixit, Ritwik Chatterjee, Rao R. Tummala, and Suresh K. Sitaraman, Microsystems Packaging Research Center, Georgia Institute of Technology, Atlanta, GA 30332-0405

9. Understanding Corner Radius (Corner Radii)
https://de.meviy.misumi-ec.com/info/en/blog-en-c/news-en-c/26940/

10. "Effect of Part Design on Injection-Molding and Plating-on-Plastic Processing", by David M. Rudder, Worldwide Plating on Plastics Support Manager, Atotech GMF, Worldwide, St. Louis, Mo., USA.
https://www.nmfrc.org/pdf/sf2007/sf0728.pdf

11. "Stress fields at sharp angular corners in thick anisotropic composite plates", by Michele Zappalorto, Paolo Andrea Carraro, Composite Structures, Volume 117, November 2014, Pages 346-353
https://doi.org/10.1016/j.compstruct.2014.06.036

12. "The Mechanical Properties of Electroplated Cu Thin Films Measured by means of the Bulge Test Technique", Yong Xiang, Xi Chen and Joost J. Vlassak, Division of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, U.S.A., Mat. Res. Soc. Symp. Proc. Vol. 695 © 2002 Materials Research Society

13. Lee, D.N., Yang, J.s. & Kang, S.y. Changes in the tensile strength and fracture mode with thickness of electrodeposited copper foil. Metals and Materials 3, 130–136 (1997).
https://doi.org/10.1007/BF03026137

"Mechanical Size Effects in Thin Copper Foils: An Experimental Study" A dissertation submitted to the SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH for the degree of Doctor of Technical Sciences presented by Gerd Simons, Dipl. Masch. -Ing. ETH, born April 27, 1975 citizen of Austria

14. How does current density affect the rate and consistency of electrodeposition? https://www.proplate.com/how-does-current-density-affect-the-rate-and-consistency-of-electrodeposition/

15. Williams, D.C., Riahi, A., Carcea, A. et al. "Hydrogen embrittlement and strain rate sensitivity of electrodeposited copper: part I – the effect of hydrogen content." npj Mater Degrad 8, 79 (2024). https://doi.org/10.1038/s41529-024-00498-y

16. Additional Discussion of general types of plating defects may be found here: https://www.sharrettsplating.com/blog/electroplating-defects-issues/#

17. "Tiny letters of exposed zinc represent plating" By Mike Diamond- Special to Coin World, COIN WORLD (USPS 120-700) (ISSN 0010-0447) is published weekly by Amos Media Company, Published: Mar 16, 2012, 8 PM https://www.coinworld.com/news/us-coins/tiny-letters-of-exposed-zinc-represent-platin.html