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Standard Guide for
Electroforming with Nickel and Copper[1]

This standard is issued under the fixed designation B832; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers electroforming practice and describes the processing of mandrels, the design of electroformed articles, and the use of copper and nickel electroplating solutions for electroforming.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.3 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
B183 Practice for Preparation of Low-Carbon Steel for Electroplating
B242 Guide for Preparation of High-Carbon Steel for Electroplating
B252 Guide for Preparation of Zinc Alloy Die Castings for Electroplating and Conversion Coatings
B253 Guide for Preparation of Aluminum Alloys for Electroplating
B254 Practice for Preparation of and Electroplating on Stainless Steel
B281 Practice for Preparation of Copper and Copper-Base Alloys for Electroplating and Conversion Coatings
B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
B343 Practice for Preparation of Nickel for Electroplating with Nickel
B374 Terminology Relating to Electroplating
B489 Practice for Bend Test for Ductility of Electrodeposited and Autocatalytically Deposited Metal Coatings on Metals
B490 Practice for Micrometer Bend Test for Ductility of Electrodeposits
B558 Practice for Preparation of Nickel Alloys for Electroplating
B571 Practice for Qualitative Adhesion Testing of Metallic Coatings
B578 Test Method for Microhardness of Electroplated Coatings
B636 Test Method for Measurement of Internal Stress of Plated Metallic Coatings with the Spiral Contractometer
B659 Guide for Measuring Thickness of Metallic and Inorganic Coatings
B849 Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement
E8 Test Methods for Tension Testing of Metallic Materials
E384 Test Method for Microindentation Hardness of Materials

3. Summary of Electroforming Practice

3.1 Electroforming is defined (see Terminology B374) as the production or reproduction of articles by electrodeposition upon a mandrel or mold that is subsequently separated from the deposit.

3.2 The basic fabrication steps are as follows: a suitable mandrel is fabricated and prepared for electroplating; the mandrel is placed in an appropriate electroplating solution and metal is deposited upon the mandrel by electrolysis; when the required thickness of metal has been applied, the metal-covered mandrel is removed from the solution; and the mandrel is separated from

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

the electrodeposited metal. The electroform is a separate, free-standing entity composed entirely of electrodeposited metal. Electroforming is concerned with the fabrication of articles of various kinds.

4. Significance and Use

4.1 The specialized use of the electroplating process for electroforming results in the manufacture of tools and products that are unique and often impossible to make economically by traditional methods of fabrication. Current applications of nickel electroforming include: textile printing screens; components of rocket thrust chambers, nozzles, and motor cases; molds and dies for making automotive arm-rests and instrument panels; stampers for making phonograph records, video-discs, and audio compact discs; mesh products for making porous battery electrodes, filters, and razor screens; and optical parts, bellows, and radar wave guides (**1-3**).[3]

4.2 Copper is extensively used for electroforming thin foil for the printed circuit industry. Copper foil is formed continuously by electrodeposition onto rotating drums. Copper is often used as a backing material for electroformed nickel shells and in other applications where its high thermal and electrical conductivities are required. Other metals including gold are electroformed on a smaller scale.

4.3 Electroforming is used whenever the difficulty and cost of producing the object by mechanical means is unusually high; unusual mechanical and physical properties are required in the finished piece; extremely close dimensional tolerances must be held on internal dimensions and on surfaces of irregular contour; very fine reproduction of detail and complex combinations of surface finish are required; and the part cannot be made by other available methods.

5. Processing of Mandrels for Electroforming

5.1 *General Considerations:*

5.1.1 Mandrels may be classified as conductors or nonconductors of electricity, and each of these may be permanent, semipermanent, or expendable (Table 1).

TABLE 1 Types of Mandrel Materials

Types	Typical Materials
Conductors	
Expendable	Low-melting point alloys; for example, bismuth-free 92 % tin and 8 % zinc
	Aluminum alloys
	Zinc alloys
Permanent	Nickel
	Austenitic Stainless
	Invar, Kovar
	Copper and brass
	Nickel-plated steel
	Nickel/chromium-plated aluminum
Nonconductors	
Expendable	Wax
	Glass
Permanent (or Semi-Permanent)	Rigid and collapsible plastic; for example, epoxy resins and polyvinyl chloride
	Wood

5.1.2 Whether or not a mandrel is a conductor will determine the procedures required to prepare it for electroforming. Conductive mandrels are usually pure metals or alloys of metals and are prepared by standard procedures but may require an additional thin parting film to facilitate separation of the electroform from the mandrel (unless the mandrel is removed by melting or chemical dissolution).

5.1.3 Whether or not a permanent or expendable mandrel should be used is largely dependent on the particular article that is to be electroformed. If no reentrant shapes or angles are involved, it is possible to use permanent, rigid mandrels that can be separated from the finished electroform mechanically and reused. If reentrant angles and shapes are involved, it is necessary to use mandrel materials that can be removed by melting or by chemical dissolution, or materials that are collapsible, such as polyvinyl chloride and other plastics. In some cases, multiple piece mandrels are used that can be removed even with reentrant features.

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[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

5.1.4 Many solid materials can be used to fabricate mandrels for electroforming, but the following generalizations may help in selecting a suitable material: permanent mandrels are preferred for accuracy and for large production runs; expendable mandrels must be used whenever the part is so designed that a permanent mandrel cannot be withdrawn; and it is important that the mandrel retain its dimensional stability in warm plating baths. Wax and most plastics expand when exposed to electroplating solutions operated at elevated temperatures. In such cases, it may be necessary to use acid copper, nickel sulfamate, and other electroplating solutions that function at room temperature.

5.2 *Mandrel Design:*

5.2.1 The electroforming operation can often be simplified by design changes that do not impair the functioning of the piece. Some of the design considerations are summarized in 5.2.2, 5.2.3, 5.2.4, 5.2.5, and 5.2.6. Examples of mandrel shapes that may present problems during electroforming are illustrated in Fig. 1.
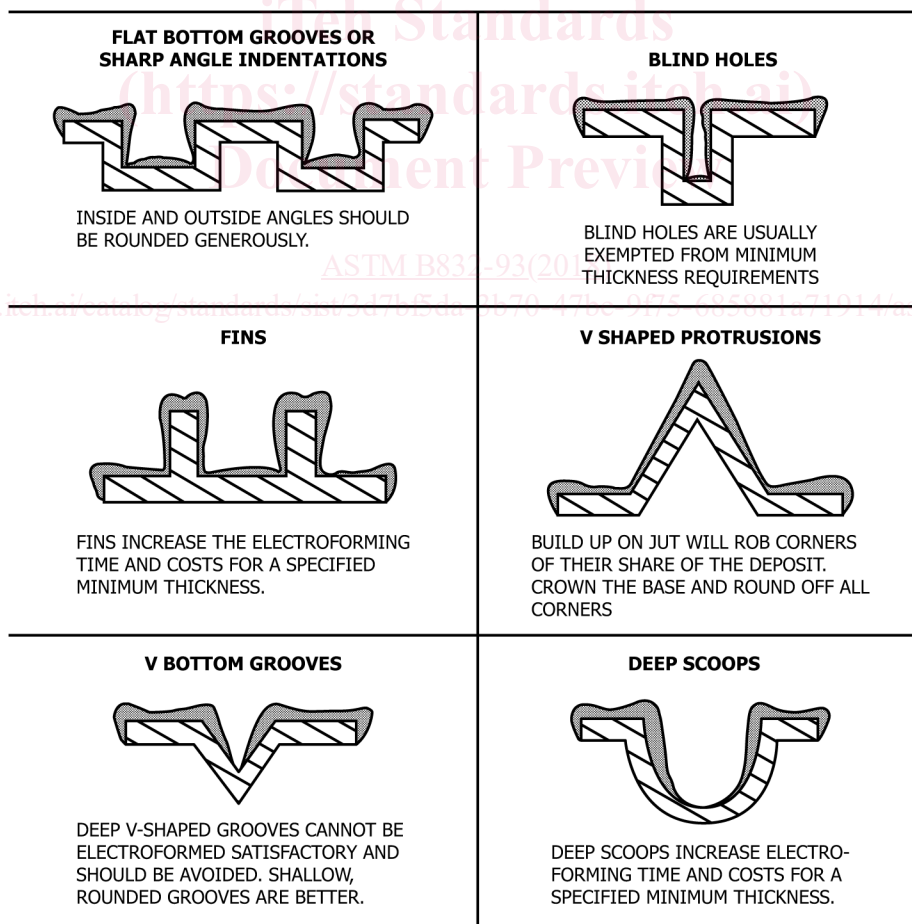
5.2.2 Exterior (convex) angles should be provided with as generous a radius as possible to avoid excessive build up and treeing of the deposit during electroforming. Interior (concave) angles on the mandrel should be provided with a fillet radius of at least 0.05 cm per 5 cm (0.02 in. per 2 in.) of length of a side of the angle.

5.2.3 Whenever possible, permanent mandrels should be tapered at least 0.08 mm per m (0.001 in. per ft) to facilitate removal from the mandrel. (Where this is not permissible, the mandrel may be made of a material with a high or low coefficient of thermal expansion so that separation can be effected by heating or cooling).

5.2.4 A fine surface finish on the mandrel, achieved by lapping or by electropolishing, will generally facilitate separation of mandrel and electroform. A finish of 0.05 µm (2 µin.) rms is frequently specified.

5.2.5 Flat bottom grooves, sharp angle indentations, blind holes, fins, v-shaped projections, v-bottom grooves, deep scoops, slots, concave recesses, and rings and ribs can cause problems with metal distribution during electroforming unless inside and outside angles and corners are rounded.

5.2.6 An engineering drawing of the mandrel, the electroformed article, and auxiliary equipment or fixture for separating the electroform from the mandrel should be prepared. The drawing of the mandrel should provide for electrical connections to be made

FLAT BOTTOM GROOVES OR SHARP ANGLE INDENTATIONS

INSIDE AND OUTSIDE ANGLES SHOULD BE ROUNDED GENEROUSLY.

BLIND HOLES

BLIND HOLES ARE USUALLY EXEMPTED FROM MINIMUM THICKNESS REQUIREMENTS

FINS

FINS INCREASE THE ELECTROFORMING TIME AND COSTS FOR A SPECIFIED MINIMUM THICKNESS.

V SHAPED PROTRUSIONS

BUILD UP ON JUT WILL ROB CORNERS OF THEIR SHARE OF THE DEPOSIT. CROWN THE BASE AND ROUND OFF ALL CORNERS

V BOTTOM GROOVES

DEEP V-SHAPED GROOVES CANNOT BE ELECTROFORMED SATISFACTORY AND SHOULD BE AVOIDED. SHALLOW, ROUNDED GROOVES ARE BETTER.

DEEP SCOOPS

DEEP SCOOPS INCREASE ELECTRO-FORMING TIME AND COSTS FOR A SPECIFIED MINIMUM THICKNESS.

NOTE 1—Examples of deposit distribution on contours that require special consideration are shown in an exaggerated fashion. The designer should confer with the electroformer before designing an electroform having any of these contours. An experienced electroformer can minimize some of the exaggeration shown.

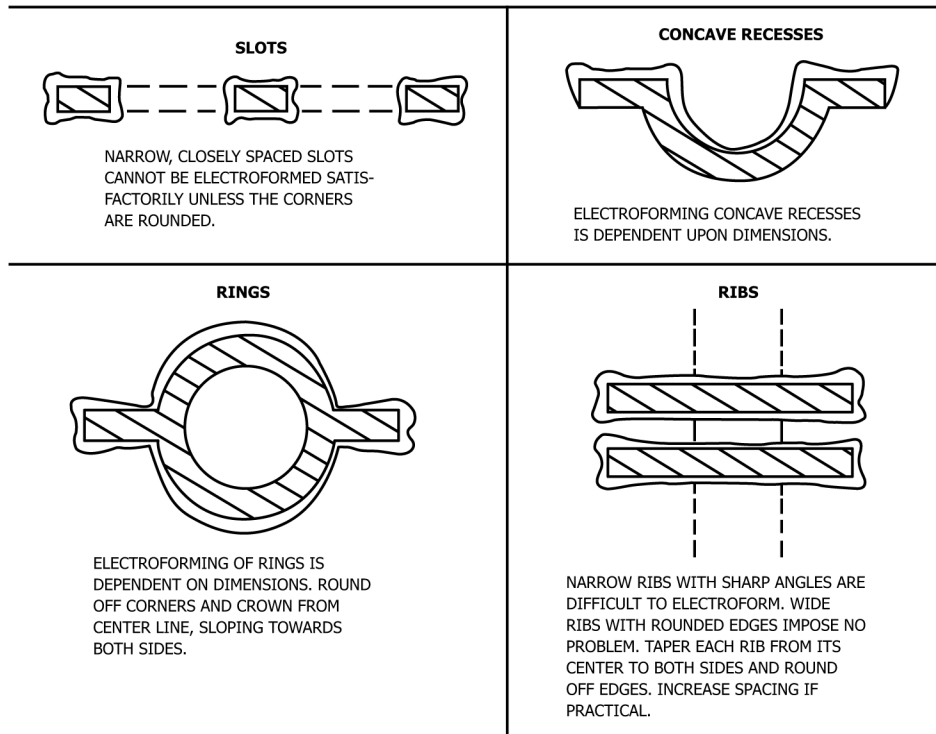**FIG. 1 Examples of Deposit Distribution on Electroforms**

SLOTS

NARROW, CLOSELY SPACED SLOTS CANNOT BE ELECTROFORMED SATIS-FACTORILY UNLESS THE CORNERS ARE ROUNDED.

CONCAVE RECESSES

ELECTROFORMING CONCAVE RECESSES IS DEPENDENT UPON DIMENSIONS.

RINGS

ELECTROFORMING OF RINGS IS DEPENDENT ON DIMENSIONS. ROUND OFF CORNERS AND CROWN FROM CENTER LINE, SLOPING TOWARDS BOTH SIDES.

RIBS

NARROW RIBS WITH SHARP ANGLES ARE DIFFICULT TO ELECTROFORM. WIDE RIBS WITH ROUNDED EDGES IMPOSE NO PROBLEM. TAPER EACH RIB FROM ITS CENTER TO BOTH SIDES AND ROUND OFF EDGES. INCREASE SPACING IF PRACTICAL.

FIG. 1 *(continued)*

in nonfunctional areas of the electroform. It should provide reference points for and mechanical means of holding if finish machining is necessary before removal of the mandrel.

5.3 *Mandrel Fabrication:*

5.3.1 The method of fabrication of the mandrel will depend on the type selected, the material chosen, and the object to be electroformed. Mandrels may be manufactured by casting, machining, electroforming, and other techniques. Permanent mandrels can be made by any of the conventional pattern-making processes.

5.4 *Preparing Non-Conducting Mandrels:*

5.4.1 Nonconducting mandrels must be made impervious to water and other processing solutions and then rendered conductive. Porous materials, for example, leather and plastic, may be impregnated with wax, shellac, lacquer, or a synthetic resin formulation. It is often preferable to use thin films of lacquer to seal porous, nonmetallic mandrels.

5.4.2 Nonconducting materials may be rendered conductive by applying a chemically reduced film of silver, copper, or nickel to the surface. In general, these processes are carried out by spraying the reagent containing the metal ions of choice simultaneously with a specific reducing agent onto the surface of the mandrel using a double-nozzle spray gun. The chemicals react at the surface; the metal is reduced and is deposited on the mandrel surface. Chemical reduction processes are preferred because dimensional accuracy is not affected, the film has little adhesion, and parting is not difficult. If necessary, a silver film can be stripped from a nickel electroform with either nitric acid, warm sulfuric acid, or a cyanide solution.

5.4.3 Other ways of making non-conducting materials conductive include: using finely divided metal powders dispersed in binders ("bronzing"), applying finely divided graphite to wax, and to natural or synthetic rubbers that have an affinity for graphite, and applying graphite with a binder.

5.4.4 Vapor deposition of silver and other metals is preferred for nonconducting mandrels used in the semiconductor industry, the optical disc industry, and the manufacture of holograms. In these cases the mandrel must be made of a material that does not outgas in the vacuum chamber. Glass is the preferred substrate for making masters and stampers for optical read-out discs of all kinds.

5.5 *Preparing Metallic Mandrels:*

5.5.1 Standard procedures should be used whenever adherent electrodeposits are applied to metallic mandrels prior to and in preparation for electroforming. See Practices B183, B242, B254, B281, and B558, for example.

5.5.2 With most metallic mandrels an additional chemical treatment that forms a parting film on the surface is required to separate the electroform from the mandrel. After removing all traces of grease and oil by means of solvents, various metallic mandrels are given different treatments for this purpose (see 5.5.3, 5.5.4, 5.5.5, 5.5.6, and 5.5.7).

5.5.3 Stainless steel, nickel, and nickel- or chromium-plated steel are cleaned using standard procedures, rinsed, and passivated by immersion in a 2 % solution of sodium dichromate for 30 to 60 s at room temperature. The mandrel must then be rinsed to remove all traces of the dichromate solution.

5.5.4 Copper and brass mandrels that have been nickel and/or chromium-plated may be treated as described in 5.5.3. If not electroplated, the surface can be made passive by immersion in a solution containing 8 g/L sodium sulfide.

5.5.5 Aluminum alloys may require special treatments even when they are used as expendable mandrels to be separated by chemical dissolution. If the deposits are highly stressed, it may be necessary to use the zincate or stannate treatments included in Guide B253 to achieve a degree of adhesion that will prevent lifting of the deposit from the mandrel. When low-stressed deposits (near zero) are being produced, treatment of the aluminum by degreasing, cathodic alkaline cleaning, and immersion in a 50 % solution of nitric acid may be sufficient.

5.5.6 Zinc and its alloys may require no other preparation than conventional cleaning if used for expendable mandrels and are to be parted by chemical dissolution. In the case of nickel electroforming, it is necessary to electroplate the zinc alloy with copper and treat it accordingly to prevent attack of the mandrel. See Practice B252.

5.5.7 The low-melting point alloys included in Table 1 employed to make expendable mandrels that can be melted away have a tendency to leave a residue of tin on the surface of the electroform. The mandrel can be plated with copper prior to electroforming to prevent this.

6. Nickel and Copper Electroforming Solutions

6.1 The choice of metal selected for the electroform will depend on the mechanical and physical properties required in the finished article as related to function. The two metals selected most frequently are nickel and copper. The operation and control of nickel and copper electroforming solutions are described in this section.

6.2 The nickel electroplating solutions commonly used for electroforming are Watts and nickel sulfamate with and without addition agents. The advantages of nickel electroforming from sulfamate solutions are the low internal stress of the deposits and the high rates of deposition that are possible. The important copper electroforming solutions are copper sulfate and copper fluoborate. The formulations of nickel electroforming solutions, typical operating conditions, and typical mechanical properties of the deposits are given in Table 2. Similar information for copper electroforming is given in Table 3.

6.3 *Watts Solutions*—The Watts bath contains nickel sulfate, nickel chloride, and boric acid and yields nickel deposits that are matte in appearance and that are tensively stressed. The solution is relatively inexpensive and is successfully used for electroforming. Nickel sulfate is the main source of nickel ions. Nickel chloride increases solution conductivity and has a beneficial effect on the uniformity of metal distribution at the cathode. Boric acid acts as a buffer to control pH at the cathode-solution interface. Antipitting agents (wetting agents) are essential for avoiding pitting due to the clinging of air and hydrogen bubbles. With care, the internal stress of the electroformed nickel can be controlled by means of organic addition agents. See 8.3.

6.4 *Nickel Sulfamate Solutions*—A formulation for nickel sulfamate solutions is included in Table 2. These are analogous to Watts solutions in which the nickel sulfate is replaced with nickel sulfamate. The internal stress is lower than in the Watts solution, as indicated by the information on mechanical properties in Table 2. The zero stress level may be obtained by maintaining the

TABLE 2 Nickel Electroforming Solutions and Typical Properties of the Deposits

	Electrolyte Composition, g/L	
	Watts Nickel	Nickel Sulfamate
$NiSO_4 \cdot 6H_2O$	225 to 300	
$Ni(SO_3NH_2)_2 \cdot 4H_2O$		315 to 450
$NiCl_2 \cdot 6H_2O$	37 to 53	0 to 22
H_3BO_3	30 to 45	30 to 45
	Operating Conditions	
Temperature, °C	44 to 66	32 to 60
Agitation	Air or mechanical	Air or mechanical
Cathode Current Density, A/dm^2	3 to 11	0.5 to 32
Anodes	nickel	nickel[A]
pH	3.0 to 4.2	3.5 to 4.5
	Mechanical Properties	
Tensile Strength, MPa	345 to 485	415 to 620
Elongation, %	15 to 25	10 to 25
Vickers Hardness, 100 g load	130 to 200	170 to 230
Internal Stress, MPa	125 to 185 (tensile)	0 to 55 (tensile)

[A] See 6.4 and 8.3.5.

TABLE 3 Copper Electroforming Solutions

	Electrolyte Composition, g/L			
	Copper Sulfate		Copper Fluoborate	
	CuSO₄·5H₂O	210–214	Cu(BF₄)₂	225–450
	H₂SO₄	52–75	HBF₄	sufficient to maintain pH at 0.2–1.5

	Operating Conditions		
Temperature	21–32°C		21–54°C
Agitation	air or mechanical		air or mechanical
Cathode current density	1–10 A/dm²		8–44 A/dm²
Anodes	wrought phosphorized copper		copper

	Mechanical Properties		
Tensile strength, MPa	205–380		140–345
Elongation,%	15–25		5–25
Hardness (Vickers hardness, 100–g load)	45–70		40–80
Internal Stress, MPa	0–10 tensile		0–105 tensile

solution in a high state of purity and by eliminating the nickel chloride. To minimize hydrolysis of nickel sulfamate and the formation of sulfate and ammonium ions, these solutions may be operated above pH 3.5 and below 50°C. To ensure efficient dissolution of nickel anodes in the absence of chlorides, it is essential to use sulfur-activated nickel anode materials. A stable tensile stress can be maintained in nickel sulfamate solutions by including nickel chloride in the formulation, by using an adequate anode area (1.5 to 2 times the area of the cathode), and by using a fully-active nickel anode material to maintain the potential on the anode basket as low as possible, thus avoiding oxidation of the sulfamate anion (see 8.3.5). Under these conditions the stress level normally is about 35 MPa (5000 psi) tensile for a well-worked solution.

6.5 *Copper Electroforming Solutions*—Copper sulfate solutions are used more often than copper fluoborate solutions. The internal stress of copper deposits is generally lower than that of electrodeposited nickel. One of the features of the fluoborate solution is the ability to electrodeposit copper at high current densities.

7. Properties of Electrodeposited Nickel and Copper

7.1 The mechanical properties—tensile strength, elongation, hardness, and internal stress—are influenced by the operational variables including temperature, pH, and current density, and by solution composition (4). The qualitative effects of these variables on the mechanical properties of nickel and copper electrodeposits are summarized in Table 4, Table 5, Table 6, and Table 7. Relatively small amounts of metallic impurities in solution can also affect mechanical properties. The properties are interrelated, and steps taken to increase the hardness of the deposit usually increase its strength and lower its ductility. The refinement of crystal structure, for example by the use of organic addition agents, is accompanied by increased hardness and tensile strength and reduced ductility. Typical properties of deposits from various additive-free baths are included in Table 2 and Table 3. See Refs. **5-7**.

7.2 The mechanical properties, especially the percent elongation or ductility, may be affected by the thickness of the electrodeposited metal used in determining the properties. For example, the ductility of nickel increases with increasing thickness up to about 250 μm after which it becomes relatively constant (8). Mechanical testing should be done at the thickness of interest even though it may be more convenient to test thick deposits.

TABLE 4 Variables that Affect Mechanical Properties of the Deposit—Acid Copper Sulfate Solution

Property	Operational	Solution Composition
Tensile Strength	Decreases slightly with increasing solution temperature.	Relatively independent of changes in copper sulfate concentration within the range suggested.
	Increases significantly with increase in cathode current density.	Relatively independent of changes in sulfuric acid concentration within the range suggested.
Elongation	Decreases with increasing solution temperature.	High acid concentration, particularly with low copper sulfate concentration, tends to reduce elongation slightly.
	Increases slightly with increasing cathode current density.	
Hardness	Decreases slightly with increasing solution temperature.	Relatively independent of copper sulfate concentration.
	Relatively independent of change in cathode current density.	Increases slightly with increasing acid concentration.
Internal Stress	Increases with increasing solution temperature.	Relatively independent of copper sulfate concentration.
	Increases with increasing carhode current density.	Decreases very slightly with increasing acid concentration.