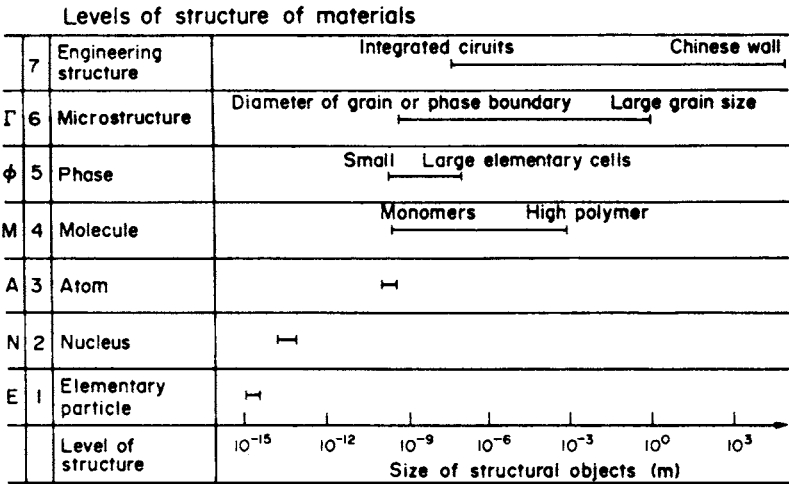


## INTRODUCTION

The properties of electrodeposits are important for a broad spectrum of applications. Safranek summarizes these along with property data in his two texts on *The Properties of Electrodeposited Metals and Alloys* (1,2). The second volume of this set (published in 1986) contains property data from over 500 technical papers published since 1971 while the first volume (published in 1974 but now out of print) covers the previous years. Both of these are an invaluable help for anyone concerned with properties of deposits. Since they are so complete, and since properties are discussed throughout this book, this chapter will be relatively short.

A fundamental concern of materials science is the relationship between structure and properties and this is true for both bulk and coated materials (3). Hornbogen (4) divides the structural level of matter into six levels (Figure 1). The interactions which occur between these different levels of structure dictate the properties of engineering materials. These interactions may start just above one atomic spacing and extend over many grains. The structure-property relationships derived for thin films reflect this complex situation. A further complication is the fact that, in general, coatings are not deposited at equilibrium and contain high concentrations of lattice vacancies, dislocations, etc., which can vary from grain to grain (3).

Before going any further it is important to distinguish between mechanical and physical properties since they are often referred to improperly. Harold Read (5) made a clear distinction in 1960 and it is still applicable today. Those properties of metals and alloys which have to do



**Figure 1:** The seven levels of structure suggested by Hornbogen (4). Reprinted with permission of Pergamon Press Ltd.

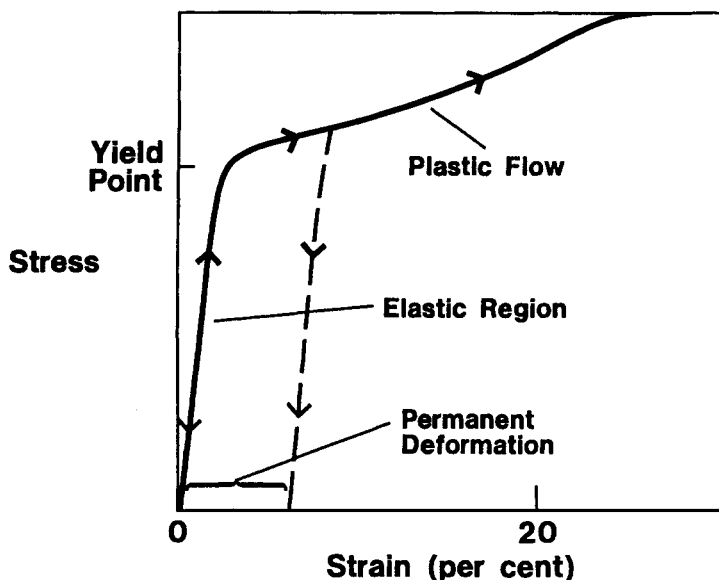
with strength, ductility, hardness, elastic modulus, and the like are properly called mechanical properties, not physical properties. The latter term is reserved for electrical conductivity, thermal conductivity, magnetic behavior, thermoelectric effects, density, melting point, lattice structure, etc. Perhaps the easiest way to divide non-chemical properties into their proper categories is simply to remember that properties which relate the deformation of a metal to a force which caused it are mechanical properties and all others are physical properties (5).

## TENSILE PROPERTIES

The practical significance of the measurement of mechanical properties lies in the use of these data to predict the performance of a material in a specific type of application. Properties obtained from tensile testing are often used for engineering purposes.

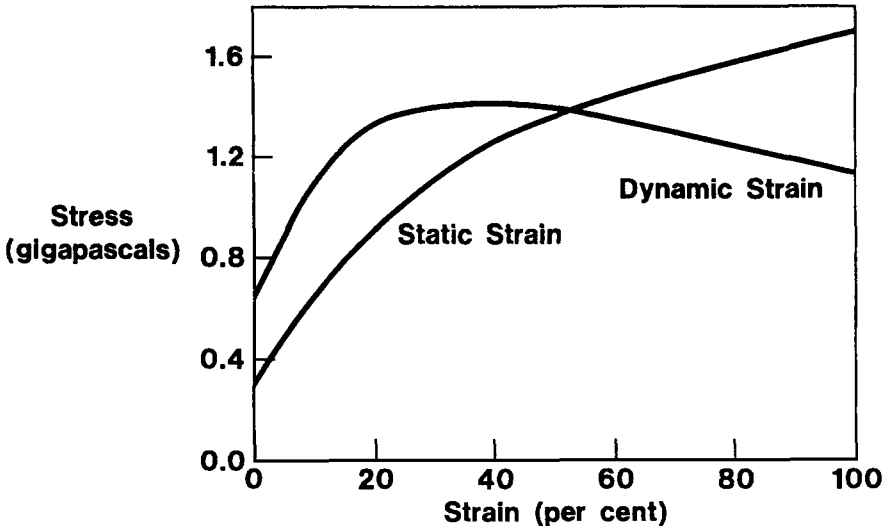
A tensile stress-strain curve is constructed from load/elongation measurements made on a test specimen (6). Typically, original dimensions are used to calculate the stress based on load measurements and dimensions of the test specimen. This disregards any thinning or necking during testing and results in what is referred to as nominal or engineering stress. The terms true stress and true strain are used when actual dimensions during testing are used in the calculations (6).

The shape of a stress-strain curve (Figure 2) is an indication of both the strength and ductility of a material. The elastic region is the early, approximately linear portion of the curve (7). In this region material that is stressed will not suffer any permanent deformation when the stress is relaxed. The onset of permanent deformation, which is a measure of yield strength, is that location where the curve leaves the elastic region by bending toward the horizontal. Beyond this is the inelastic or plastic flow region of the curve. The slope of the curve in each region provides information: in the elastic region it is the elastic modulus which is a measure of the material's stiffness and in the plastic flow region it is a



**Figure 2:** A representative stress-strain curve. Adapted from reference 7.

measure of work hardening since a steeper slope means more stress must be applied to create a given amount of deformation (7). Figure 3 shows the influence of strain rate on the strength and behavior of depleted uranium. Stress-strain curves are presented at strain rates of 5000 (dynamic) and 0.001 per second (static). The dynamic, or high strain rate curve reveals a higher yield point and, initially higher work hardening, followed by lower work hardening as the material thermally softens (7). Crack-free chromium is an example of an electrodeposit with a low strain hardening rate. With this low strain hardening rate, rapid localization of deformation occurs and this leads to early fracture and an increased wear rate unlike the behavior noted for conventional chromium deposits (8,9).



**Figure 3:** Stress-strain curves for depleted uranium at strain rates of 5000 (dynamic) and 0.001 per second (static). Adapted from reference 7.

The tensile strength of individual electrodeposited metals spans broad ranges and depends on the conditions adopted for electrodeposition (2). This is shown in Table 1 which compares strength of electrodeposits with their annealed, metallurgical counterparts of comparable purity. In a number of cases, the electrodeposit is two or three times as strong as the corresponding wrought metal. The maximum tensile strength for electrodeposited cobalt is more than four times the strength of annealed, wrought cobalt while some chromium deposits are nearly seven times as strong as cast or sintered chromium. A fine grain size is the primary reason for the higher strength of the electrodeposits as compared with their wrought counterparts (2). An example is electrodeposited gold containing 0.6 at% cobalt. This deposit has a hardness ( $VHN_{10} = 190$ ) about four times that of annealed bulk gold and this high hardness cannot be reproduced by standard metallurgical methods. The fine grain size ( $250\text{--}300\text{\AA}$ ) of the electrodeposited gold accounts for the observed high hardness. Other mechanisms such as solution hardening, precipitation hardening, strain hardening, and "voids" hardening account for only small alterations in the hardness of this coating (10).

The high strengths and hardnesses, high dislocation densities, fine grain structure, and response to heating obtained with electrodeposited metals are due to the existence of a strained condition similar to that found in cold worked metals. Figure 4, a plot of recrystallization temperature for electrodeposited pyrophosphate copper and wrought copper with various

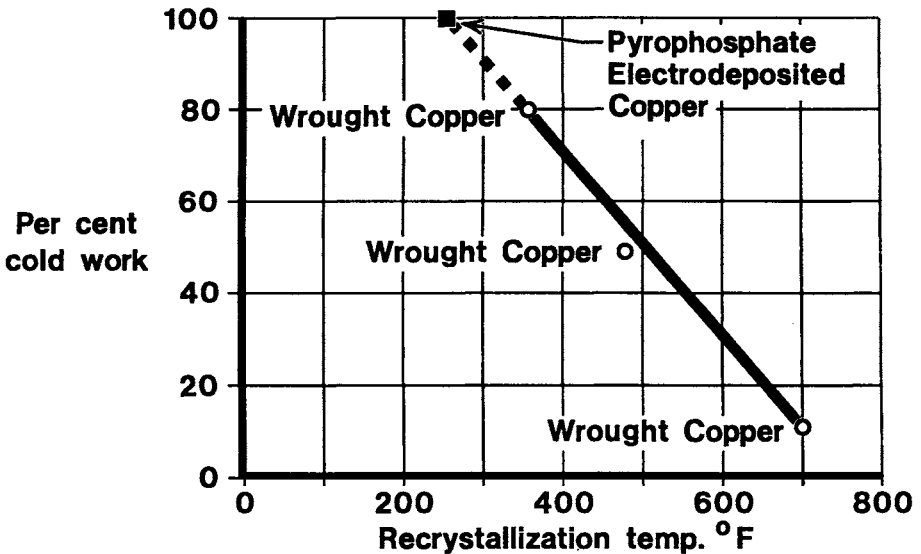
**Table 1: Strength and Ductility Data for Electrodeposited Metals and Their Wrought Counterparts (Ref. 2)**

<u>Metal</u>	<u>Plating Bath</u>	<u>Minimum Tensile Strength</u>	<u>Maximum Tensile Strength</u>	<u>Elongation, percent</u>	<u>Wrought Metal<sup>(a)</sup></u>	
					<u>psi</u>	<u>psi</u>
Aluminum	Anhydrous chloride-hydride-ether	11,000	31,000	2 to 26	13,000	35
Cadmium	Cyanide	-	10,000	-	10,300	50
Chromium	Chromic acid	14,000	80,000	<0.1	12,000	0
Cobalt	Sulfate-chloride	76,500	172,000	<1	37,000	-
Copper	Cyanide, fluoborate, or sulfate	25,000	93,000	3 to 35	50,000	45
Gold	Cyanide and cyanide citrate	18,000	30,000	22 to 45	19,000	45
Iron	Chloride, sulfate, or sulfamate	47,000	155,000	2 to 50	41,000	47
Lead	Fluoborate	2,000	2,250	50 to 53	2,650-3,000	42 to 50
Nickel <sup>(b)</sup>	Watts, and other type baths	50,000	152,000	5 to 35	46,000	30
Silver	Cyanide	34,000	48,000	12 to 19	23,000-27,000	50 to 55
Zinc	Sulfate	7,000	16,000	1 to 51	13,000	32

<sup>a)</sup>Annealed, worked metal

<sup>b)</sup>Data do not include values for nickel containing >0.005% sulfur

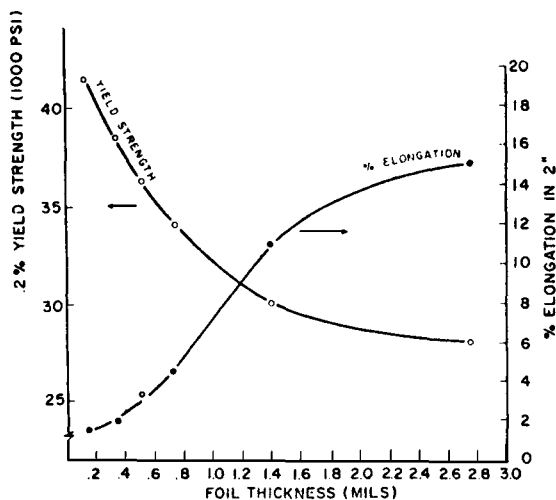
degrees of cold work suggests that the electrodeposited copper exhibits behavior expected of 100% cold worked material (11). The higher the percentage of cold work, or strained condition, the quicker the recrystallization behavior upon heating. Other examples comparing electrodeposits with cold worked counterparts include copper deposited in acid solution containing thiourea and electrodeposited silver. Dislocation density of the copper deposits (12) was  $3 \times 10^{11}/\text{cm}^2$  compared to  $2 \times 10^{11}/\text{cm}^2$  for cold worked copper (13) and the stored energy of cold worked silver reduced in cross section by 87% was of the same order of magnitude of that of electrodeposited silver (14).



**Figure 4:** Recrystallization temperature for various copper materials. Adapted from reference 11.

## STRENGTH AND DUCTILITY OF THIN DEPOSITS

It's important to realize that tensile strength and ductility of thin deposits are very much influenced by the thickness of the test sample. Typically, tensile strength data are high for thin deposits and then decrease as a function of thickness before reaching some steady value while elongation data show the opposite. The effect on elongation is generally more pronounced than on tensile strength. Figure 5 and Table 2 show this effect for thick copper (0.2 to 3.0 mil) and nickel (5.5 to 144 mil) deposits respectively (15,16). This decrease in tensile strength and increase in



**Figure 5:** Influence of thickness on yield strength and elongation of electrodeposited copper. From reference 15.

**Table 2: Influence of Thickness of Sulfamate Nickel Deposits on Tensile and Ductility Properties (From Ref. 16)**

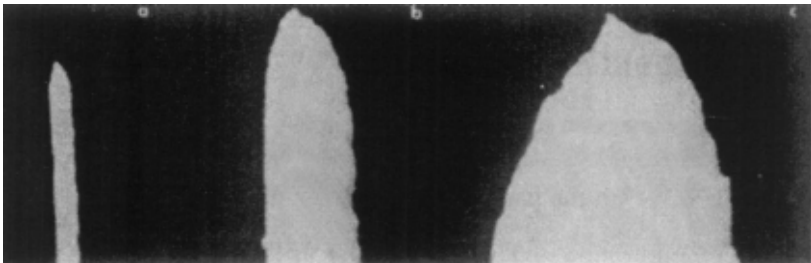
Thickness (mils)	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	RA (%)
5.5	47 700	87 400	-	-
8.3	38 400	80 700	-	-
15	-	77 100	10.9	90.8
20	-	76 800	12.1	93.9
29	39 600	74 700	12.6	94.4
54	38 700	70 900	-	-
91	33 200	71 000	31.8	90.8
144	37 600	70 900	29.2	88.4

elongation with thinner deposits reflects a change in necking behavior whereby the thinner foils undergo less plastic flow at a given strain level (17).

Ductilities, as evidenced by percent elongation, are higher when the deposits are attached to their substrates since they cannot exhibit highly localized plastic deformation prior to fracture (18). The lower ductilities of the foils tested without their substrates are probably caused by the more severe local plastic deformation in the region where fracture subsequently occurs. This localized plastic deformation is called necking. When samples neck, this covers an appreciable portion of the cross sectional area so they break. Nickel electrodeposits (19) and electroless copper (20) have been found to exhibit severe necking when tested without their substrates.

In cases where it is possible, a better indicator of ductility is measurement of the reduction of area of the sample rather than elongation (17). Reduction of area is largely a measure of the inherent ultimate ductility of a material whereas elongation is largely a practical measure of stretching capability during forming; it is dependent on specimen shape and dimensions as well as on inherent ductility. Figure 6 shows three gold samples of varying thickness (1, 4, and 10 mils) after tensile testing. They all exhibit similar reduction in area values, e.g. greater than 95%, however, elongations varied from 5% for the 1 mil sample, to 11 % for the 4 mil sample to 23% for the 10 mil sample. The cross sections clearly show they were all equally ductile. This is a good example revealing that reduction in area measurements or metallographic cross section evaluation of a sample after fracture can give a better evaluation of the extent of necking strain.

Conventional tensile testing machines are used for samples with width-to-thickness ratios around 500. They are not suitable for thin foils with width-to-thickness ratios of 20, such as found on printed wiring boards (21). A new tensile testing machine developed under AESF Project 38 can



**Figure 6:** Gold deposits of varying thickness after tensile testing; a) 1 mil, 5% elongation, b) 4 mils, 11% elongation, and c) 10 mils, 23% elongation. As can be seen above, all exhibited greater than 95% reduction in area.



test samples as thin as 2000Å, which is only about 1000 atom layers (22,23). Mechanical properties of thin nickel deposits tested on this machine are shown in Table 3. Very thin deposits exhibited the highest yield strengths and this property decreased with increasing thickness. The high yield strength of the thinnest deposit is probably due to surface pinning of dislocations. The tensile strengths are seen to be relatively unaffected by the thickness of the deposits. Elongation increased with increasing thickness because a larger portion of the gage length deformed plastically, with all deposits necking down to essentially the same thickness prior to fracture (23).

**Table 3: Mechanical Properties of Thin Nickel Deposits<sup>1</sup>**

Thickness ( $\mu\text{m}$ )	Young's Modulus (GPa)*	Yield Strength (MPa) #	Tensile Strength (MPa)	Percent Elongation
0.2	80 (3)	220 (5)	220 (5)	0
2.0	92 (1)	154 (3)	200 (5)	2.2 (0.2)
4.2	92 (0)	137 (7)	190 (6)	3.7 (0.2)
5.7	87 (1)	130 (11)	200 (7)	6.2 (0.2)
7.5	86 (3)	122 (8)	210 (13)	7.0 (0.1)
8.3	84 (2)	130 (8)	204 (4)	7.0 (0.3)
9.5	85 (2)	123 (7)	205 (5)	7.0 (0.2)

<sup>1</sup> From reference 23. Each value is the average of at least three measurements. The values in parenthesis are the variations on the individual measurements.

\* 7 GPa = approximately 1 million psi

# 7 MPa = approximately 1000 psi

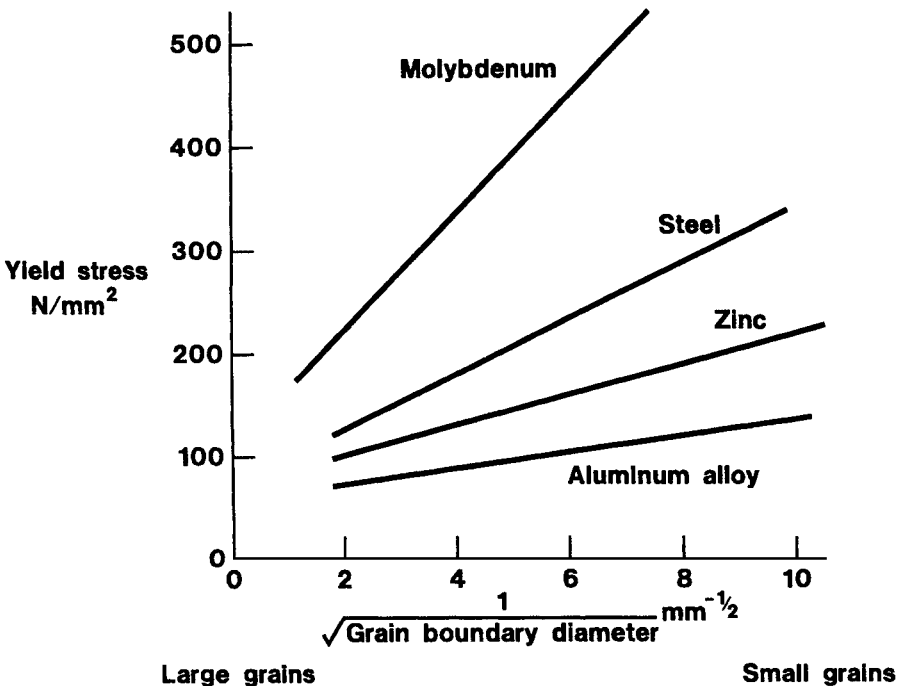
## HALL-PETCH RELATIONSHIP

There have been several attempts to relate grain size of a metal with its mechanical properties. One of these, the Hall-Petch (24) equation relates the grain size,  $d$ , with the hardness,  $H$ , of a metal:

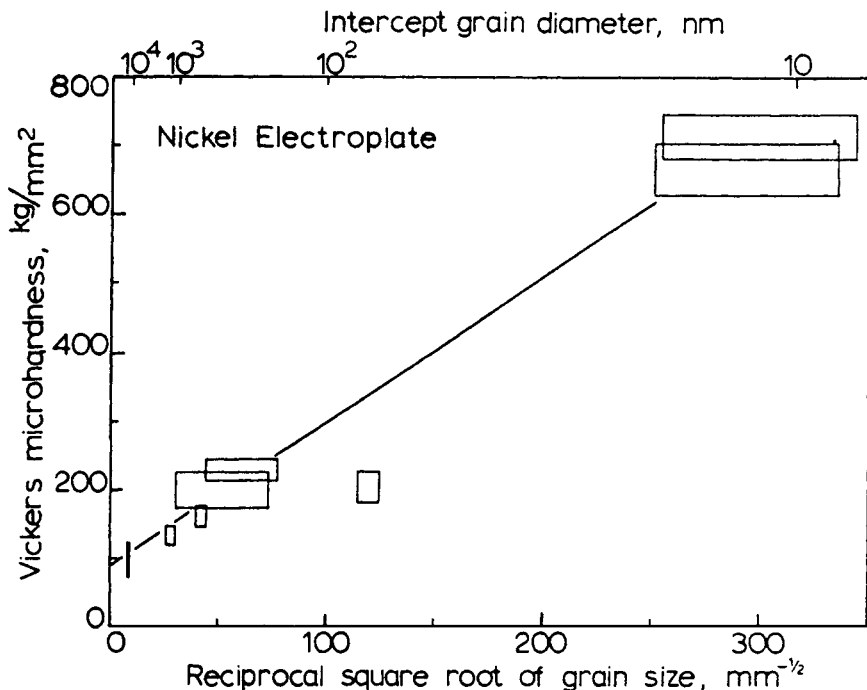
$$H = H_o + K_H d^{-1/2}$$

The terms,  $H_o$  and  $K_H$  are experimental constants and are different for each metal.  $H_o$  is the value characteristic of dislocation blocking and is related

to the friction stress.  $K_H$  takes account of the penetrability of the boundaries to moving dislocations and is related to the number of available slip systems (25). The equation has been found applicable to several polycrystalline materials as shown in Figure 7 (26), and also for electrodeposited iron (27), nickel (28,29) and chromium (30). Hall-Petch strengthening is shown in Figure 8 for electrodeposited nickel over a range of grain sizes from 12,500nm down to 12nm. A microhardness of approximately 700 kg/mm<sup>2</sup> was obtained with the smallest grain size (28). A Hall-Petch analysis has been used to help in understanding the occurrence of brittle cracking in chromium electrodeposits. An appreciable friction stress resistance to dislocation movement was shown to exist within the grain volumes of electrodeposited chromium and such friction strength strengthening for body centered cubic materials normally promotes brittleness (30). Hardness and grain size values for copper electrodeposits have also been analyzed using the Hall-Petch equation, but a better correlation was found using a semilogarithmic relationship (25).



**Figure 7:** Hall-Petch relationship for a variety of metals. Adapted from reference 26.

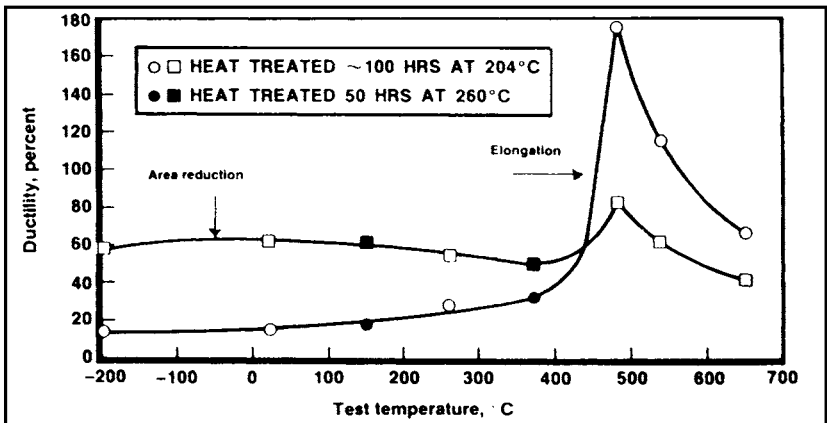


**Figure 8:** Microhardness dependence of electrodeposited nickel on reciprocal square root of grain size; rectangles define 95% confidence limits. From reference 28. Reprinted with permission of Pergamon Press Ltd.

## SUPERPLASTICITY

The behavior of substances such as taffy and glass when they are heated to their softening point and gently pulled is noticeably plastic. These materials can be stretched to many times their original length and retain the new shape after they have cooled (31). A piece of metal under tension typically breaks before it reaches twice its original length, unless it is squeezed as it deforms (as it is in the drawing of wire) to counteract its tendency to "neck down" and break. Within the last twenty-five years, however, a number of alloys have been discovered that will behave like taffy or glass if certain significant steps are taken in their processing. This phenomenon is referred to as superplasticity and it offers the possibility of forming complicated shapes at high temperatures, while also increasing their room temperature strength, ductility and ability to be machined.

Superplasticity refers to large tensile elongations, typically 500%, that can be achieved in polycrystalline materials under certain conditions of strain rate and temperature. One of the main requirements for superplasticity is the presence of an ultrafine, equiaxed microstructure, typically 1 to 5  $\mu\text{m}$  diameter, that remains stable while being deformed at the superplastic temperature (usually around one-half the melting point) (32). This small grain size is typical of many electrodeposited metals, thus offering the exciting prospect that one could fabricate complex parts by combining preforming by electrodeposition and final forming of the internal structure by superplastic deformation. However, what isn't known for most electrodeposited metals is how stable these grain sizes are at temperatures around one-half their melting points. Two electrodeposited alloys which meet these requirements and, therefore, exhibit superplastic behavior are Cd-Zn (33) and Ni/40 to 60 percent Co (34,35). Elevated temperature ductility of Ni/45 to 56 percent Co is shown in Figure 9. A ductility peak occurs at 482 C (900 F), where Ni-Co exhibits superplastic behavior. A 280 percent elongation has been obtained over the central area of reduced test sections and significantly higher elongations may be possible since the process has not been optimized (34,35).



**Figure 9:** Average ductility of Ni-Co with 45 to 56 percent Co as a function of test temperature. From reference 34. Reprinted with permission of American Electroplaters & Surface Finishers Soc.

Although a number of alloys exhibit superplastic behavior, lead-tin (36,37), copper-nickel (38), and cadmium-tin (39) are three of particular interest since these can be deposited from aqueous solution. One technique that was used to produce superplastic lead-tin alloys was the deposition of alternate layers of 0.5 to 5  $\mu\text{m}$  thick (36), and this approach could be used

to produce a variety of electrodeposited alloys.

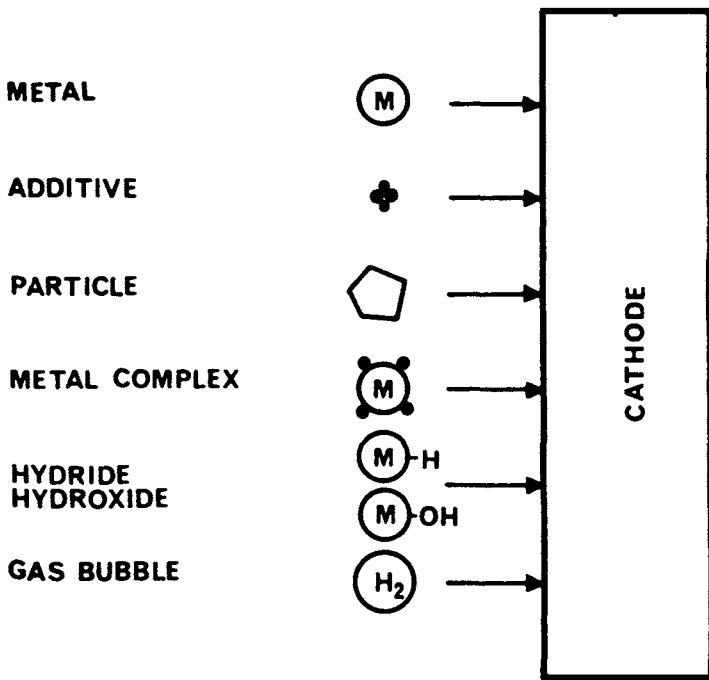
The burgeoning field of electrodeposition of multilayer coatings by cyclic modulation of the cathodic current or potential during deposition (40) also offers promise for production of new superplastic alloys. Composition-modulated alloys (CMA) which have been produced by this process include Cu-Ni, Ag-Pd, Ni-NiP, Cu-Zn and Cu-Co. At present, no data on superplasticity of these alloys have been obtained, however, the room temperature tensile strength of CMA Ni-Cu alloys has been shown to exhibit values around three times that of nickel itself (41).

## INFLUENCE OF IMPURITIES

Electrodeposited films contain various types of inclusions which typically originate from the following sources: 1-deliberately added impurities, i.e., organic or organometallic additives (addition agents), 2-metallic or nonmetallic particles for composite coatings, 3-intermediate cathodic products of complex metal ions, 4-hydroxides or hydroxides of a depositing metal, and 5-gas bubbles, for example, containing hydrogen (42). Figure 10 provides a pictorial illustration of these various types of inclusions. Much has been written on the influence of small amounts of inclusions on the appearance of deposits. However, very little information is available on their influence on properties of deposits. The purpose of this section is to provide examples showing how small amounts of impurities can noticeably affect properties.

With nickel, low current density deposits have higher impurity contents and this can affect stress and other properties. For example, Table 4 shows that for nickel sulfamate solution, hydrogen and sulfur contents are much higher for low current density deposits ( $54 \text{ A/m}^2$ ) than for those produced at higher current densities (43). Electrical resistance of electroformed nickel films shows a unique dependence on plating current density (Figure 11). Films deposited at a low current density of  $120 \text{ A/m}^2$  show considerably lower residual resistance than high current density films over the temperature range of 4 to 40 K presumably due to codeposited impurities in the low current density deposits (44).

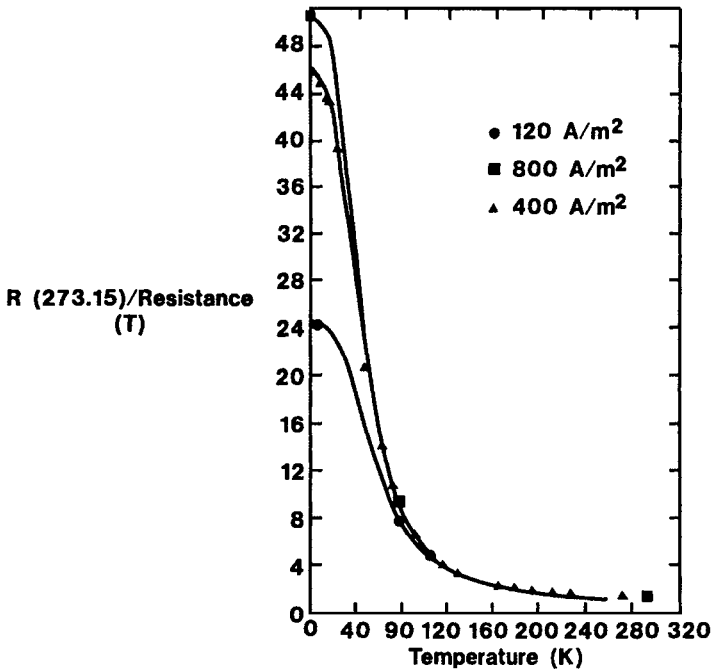
Small amounts of carbon in nickel and tin-lead electrodeposits can noticeably influence tensile strength. For example, increasing the carbon content of a sulfamate nickel electrodeposit from 28 to 68 ppm increased the tensile strength from 575 to 900 MPa, a noticeable increase in strength with a few ppm of the impurity (45). Similarly, with tin-lead, increasing the carbon content of the electrodeposit from 125 to 700 ppm increased the tensile strength from 29 to 41 MPa (46). Carbon also increases the strength



**Figure 10:** A pictorial representation of the various types of inclusions in electrodeposited films. From reference 42. Reprinted with permission of The Electrochemical Soc.

**Table 4: Influence of Current Density in Nickel Sulfamate Solution on Impurity Content of Deposits (Ref 43).**

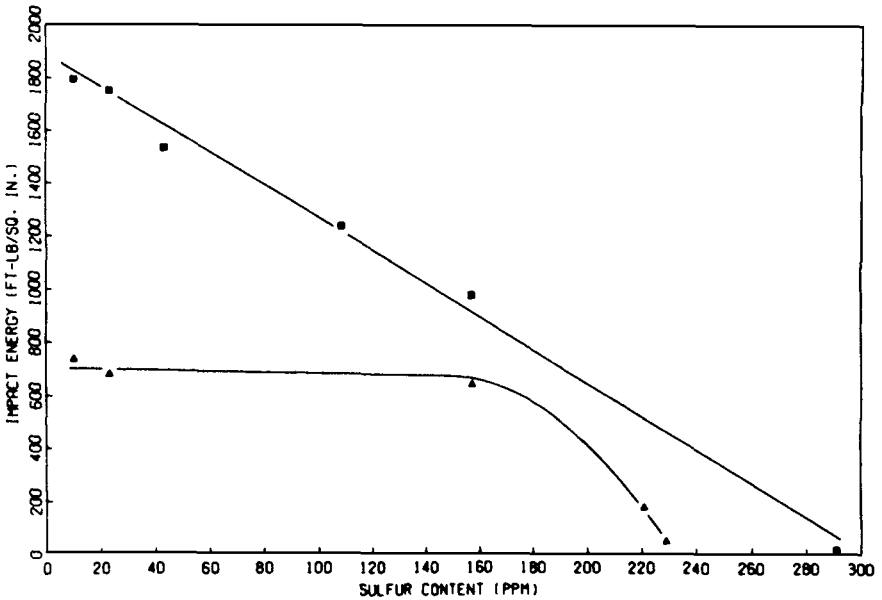
Current Density			Impurity content (ppm)			
(A m <sup>-2</sup> )	(A ft <sup>-2</sup> )	C	H	O	N	S
54	5	70	10	44	8	30
323	30	80	3	28	8	8
538	50	60	4	32	8	6



**Figure 11:** Resistance-temperature curves for electrodeposited nickel films approximately 20  $\mu\text{m}$  thick. Adapted from reference 44.

of cast nickel and nickel-cobalt alloys but the effect isn't as pronounced as that for electrodeposits. For example, increasing the carbon from 20 to 810 ppm in cast nickel increases the flow stress from 190 to 250 MPa (47).

Sulfur impurities can be harmful to nickel deposits which are intended for structural or high temperature usage. For example, small amounts of codeposited sulfur can noticeably influence notch sensitivity, hardness and high temperature embrittlement. Charpy tests, which are impact tests in which a center-notched specimen supported at both ends as a simple beam is broken by the impact of a rigid, falling pendulum, showed that deposits containing greater than 170 ppm of sulfur were highly notch sensitive (48,49). Figure 12 shows the results of testing specimens of two different thicknesses, 0.51 cm (0.200 in), and 0.19 cm (0.075 in). An increase in sulfur content is clearly shown to reduce the fracture resistance of electroformed nickel. Whereas thicker specimens (0.51 cm) displayed a steady decrease of impact energy with sulfur content, thinner specimens (0.19 cm) maintained roughly constant impact energy values up to 160 ppm. In this case, the thinner specimens were in a plane stress condition typified by shear fractures and relative insensitivity to sulfur content. In contrast, the



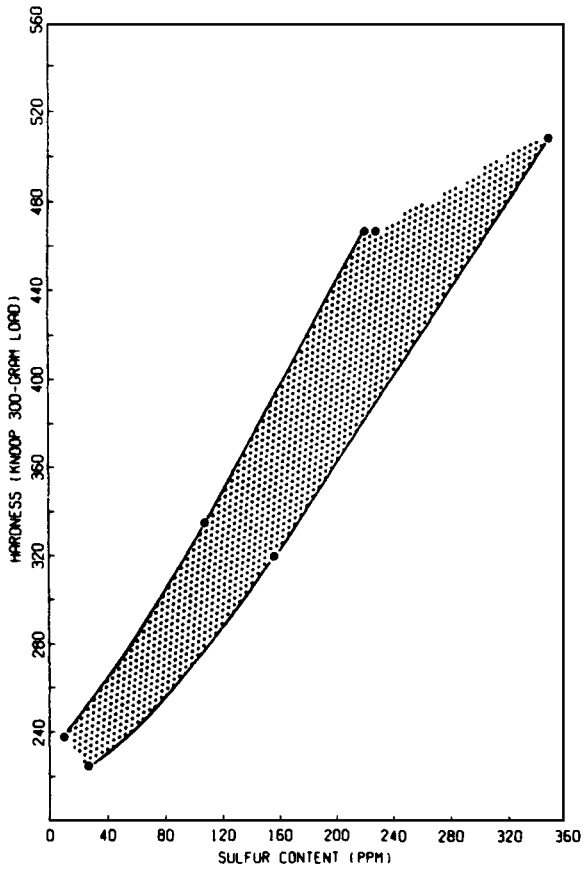
**Figure 12:** Influence of sulfur content on impact strength of electroformed sulfamate nickel. The squares are 0.200 in. (0.51 cm) thick Ni and the triangles are 0.075 in. (0.19 cm) thick Ni. Adapted from reference 48.

plane strain condition (no strain in the direction perpendicular to the applied stress and crack length, reference 50) existing in thicker specimens led to higher triaxial tensile states and a significant sensitivity to sulfur content. Sulfur also has a direct influence on the hardness of electrodeposited nickel (Figure 13), therefore, if no other impurities are present in the deposit, hardness can be used as an indicator of sulfur content (48,49).

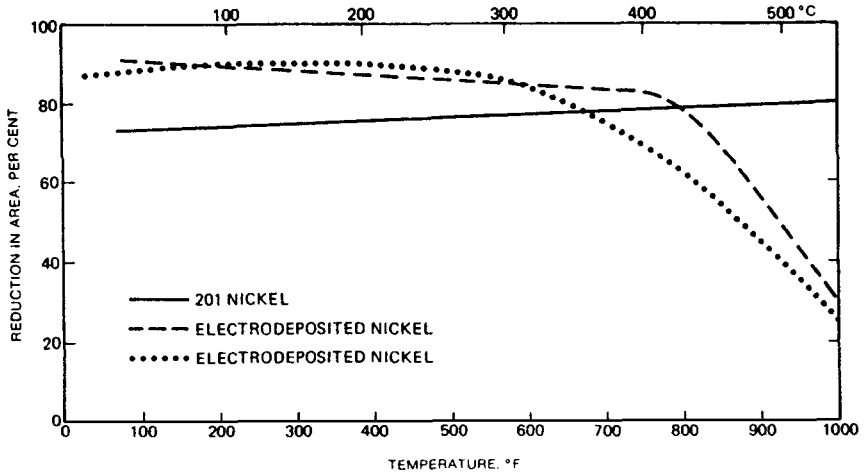
## HIGH TEMPERATURE EMBRITTLEMENT OF NICKEL AND COPPER

Both nickel and copper electrodeposits undergo a ductile to brittle transition at high temperature. With nickel, reduction in area drops from greater than 90% at ambient to around 25% at a test temperature of 500 C (Figure 14, ref 51). This effect occurs at a much lower temperature for copper electrodeposits, e. g., 100 to 300 C depending on the conditions used for electrodeposition (Figure 15, ref 52).

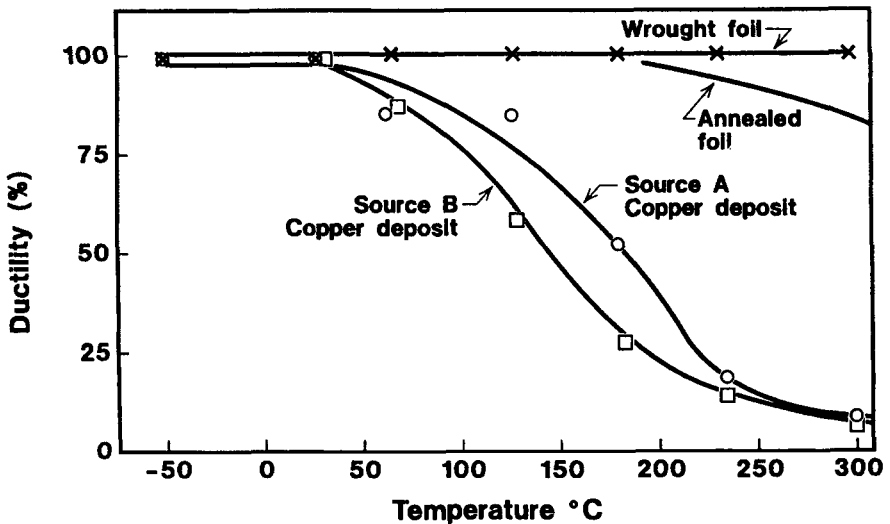




**Figure 13:** Influence of sulfur content on hardness of electroformed nickel. Adapted from reference 49.



**Figure 14:** Influence of temperature on reduction in area of 201 nickel and electrodeposited sulfamate nickel. Adapted from reference 51.



**Figure 15:** Influence of temperature on reduction in area for OFE (oxygen free electronic) copper and electrodeposited copper. Adapted from reference 52.

Electrodeposited nickel is quite pure, especially when compared with 201 wrought nickel which does not exhibit the ductile to brittle transition (Table 5 and Figure 14). The problem is that the electrodeposited nickel is too pure. Embrittlement occurs because of formation of brittle grain boundary films of nickel sulfide. Wrought 201 nickel doesn't exhibit the problem because it has sufficient manganese to preferentially combine with the sulfur and prevent it from becoming an embrittling agent. By codepositing a small amount of manganese with the nickel, the embrittling effect can be minimized. The amount of manganese needed to prevent embrittlement depends on the heat treatment temperature. The Mn:S ratio varies from 1:1 for 200 C treatments to 5:1 for 500 C treatments (51,53).

Embrittlement in electrodeposited copper is also probably due to grain boundary degradation stemming from the codeposition of impurities during electroplating. It's speculated that impurities modify the constitutive behavior or produce grain boundary embrittlement that leads to plastic instability and failure at small overall strains when compared with cast or wrought material of comparable grain size (54). At present the culprits have not been identified but two likely candidates are sulfur and oxygen. For example, cast high purity copper (99.999+%) is embrittled at high temperature when the sulfur content is greater than 4 ppm (55). Oxygen in cast copper has also been reported to cause embrittlement at high temperatures, either under tensile or creep conditions (56). This embrittlement is attributed to oxygen segregation to grain boundaries in the copper which promotes grain boundary decohesion and enhances intergranular failure. Both sulfur and oxygen can be present as impurities in electrodeposited copper.

## **OXYGEN IN CHROMIUM DEPOSITS**

The relationship between the internal stress in chromium deposits and their oxygen content is shown in Figure 16. The broad band depicts the scatter observed in many hundreds of experiments (57). These variations are not unexpected because residual stress in any situation is related to the well known cracking of chromium deposits. The changes were achieved by changing the solution compositions at constant temperature (86 C) and current density (75 A/dm<sup>2</sup>).

## **PHYSICALLY VAPOR DEPOSITED FILMS**

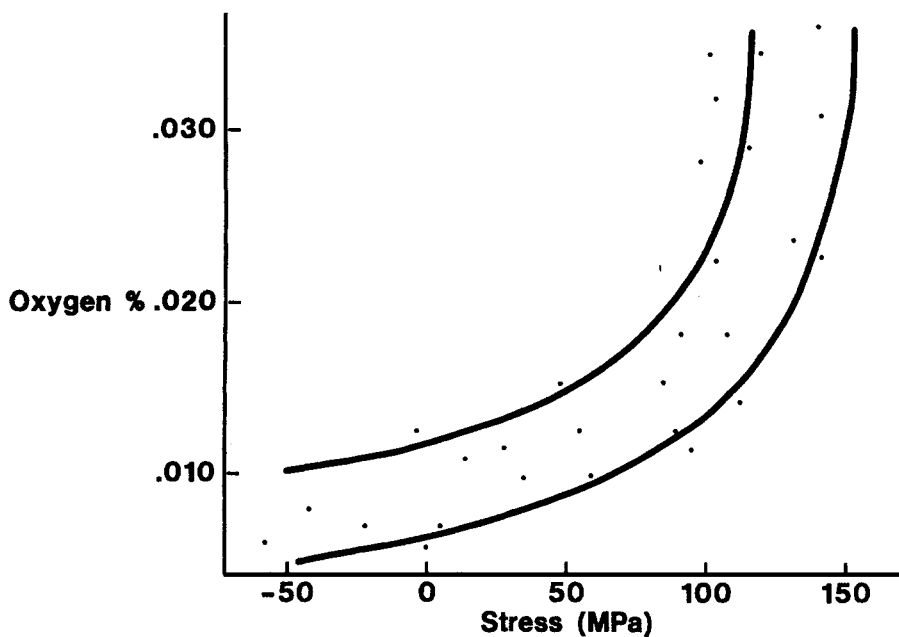
With physically vapor deposited films, certain long term stability problems may be due to gas incorporation during deposition (58). In sputter

**Table 5: Composition of 201 Nickel and Electrodeposited Sulfamate Nickel**

<u>Element</u>	<u>201 Nickel (ppm)</u>	<u>Electrodeposited Nickel<sup>1</sup> (ppm)</u>
Copper	250 max	<100
Iron	400 max	<100
Manganese	3500 max	< 5
Silicon	3500 max	< 10
Carbon	93	50
Cobalt	4700	1000
Hydrogen	2	8
Oxygen	17	20
Nitrogen	6	6
Sulfur	12	10

<sup>1</sup> Composition of the nickel sulfamate plating solution was 80 g/l nickel (as nickel sulfamate), <1.0 g/l nickel chloride, and 40 g/l boric acid. Wetting agent was used to reduce the surface tension to 35-40 dynes/cm. Current density was 268 A/m<sup>2</sup>; pH, 3.8; and temperature, 49°C. Anodes were sulfur depolarized nickel.

deposition, up to several atomic percent of atoms of the sputtering gas can be incorporated into the deposited film and this gas can precipitate into bubbles or be released by heating (59-64). The incorporated gas can increase the stress and raise the annealing temperature of sputter deposited gold films (59). Argon incorporation up to 1.5 at. % is possible in TiC films and this causes compressive stresses of the order of 10<sup>7</sup> Pa. Such high stresses give rise to lattice distortion which affects the dislocation properties and thus the hardness of the films (60). Similar effects are found in electron beam evaporated films where residual gases, often released by heating during evaporation, are incorporated into the deposit and may cause property changes (64).



**Figure 16:** Influence of oxygen on stress in chromium electrodeposits produced at 86°C and 75 A/dm<sup>2</sup>. Adapted from reference 57.

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