BRUSH WELLMAN TECHNICAL EXCHANGE

CONNECTOR ENGINEERING DESIGN GUIDE

Material Selection In The Design Of Spring Contacts And Interconnections

Table of Contents | List of Tables | List of Charts | List of Figures

Technical Exchange

Design Guide - Appendix

Design Guide - Introduction

Design Guide - Table of Contents

TABLE OF CONTENTS

LIST OF TABLES

LIST OF CHARTS

Technical Exchange

Design Guide - List of Tables

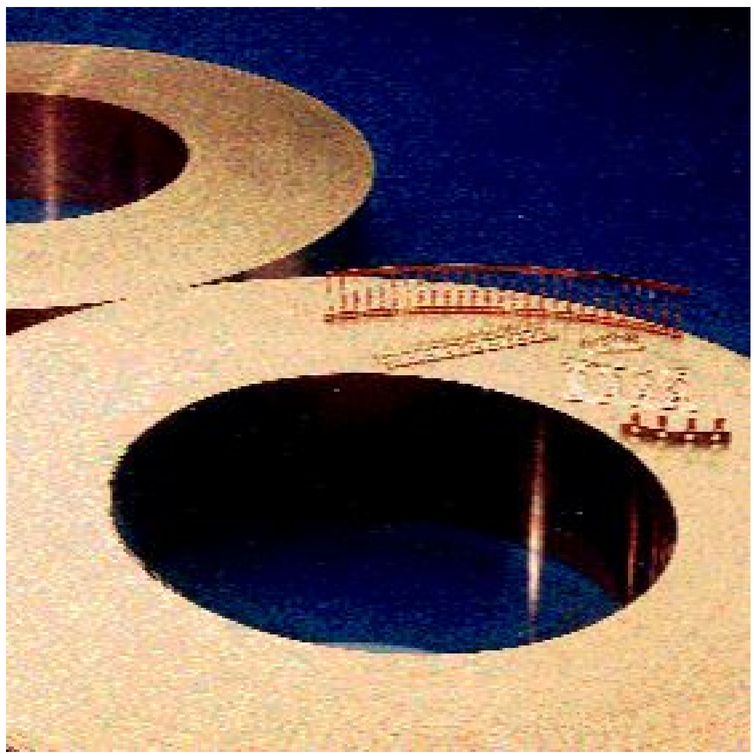
Design Guide - List of Figures

Design Guide

LIST OF FIGURES

iNTRODUCTiON

Contact materials possess varying combinations of strength, stress relaxation resistance, conductivity, formability, corrosion resistance and magnetic permeability. Choosing an alloy that best meets the complex needs of a new contact application requires an awareness of the characteristics and interrelationships governing material performance. This awareness is dependent on the designer's knowledge of the available alloys and their specific performance, manufacturing, quality and cost effectiveness characteristics.



In its capacity as a fully integrated supplier of beryllium-containing alloys, Brush Wellman's technological expertise spans the full spectrum of these alloys in strip, rod, wire, bar, plate, fabricated forms, casting and master alloys. Considering this total capability, Brush Wellman has structured this Design Guide to facilitate the design process by providing a framework from which you can:

- Determine the general class of alloy necessary to fulfill the requirements of a connector application.
- Determine the temper that provides the optimum solution to the application's operating and manufacturing parameters.

This Design Guide includes the manufacturer's published material properties and testing conducted by Brush Wellman for the alloys shown in Table 3.

The material characteristics and properties of the beryllium copper alloys, presented in blue, demonstrate the available performance range obtainable with these products. In addition to its standard products, Brush Wellman manufactures custom materials specifically tailored to customer specifications.

A Word About Navigation

The provides context-sensitive navigation. See the bottom of all pages for help on where it will take you.

All technical figures have enlargements. To view an enlargement, click on the figure or its associated hypertext link. To return to the main text, click on the enlarged figure, click on the bottom of the compass, or use your browser's Back button.

All tables have enlargements. To view an enlargement, click on the hypertext link for the table. To return to the main text, use your browser's Back button.

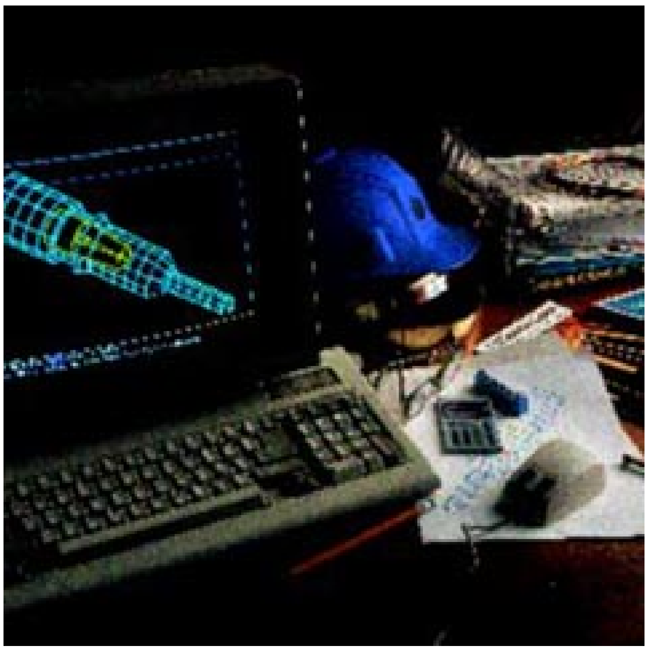
Technical Exchange

Design Guide - Appendix

Design Guide - Section I

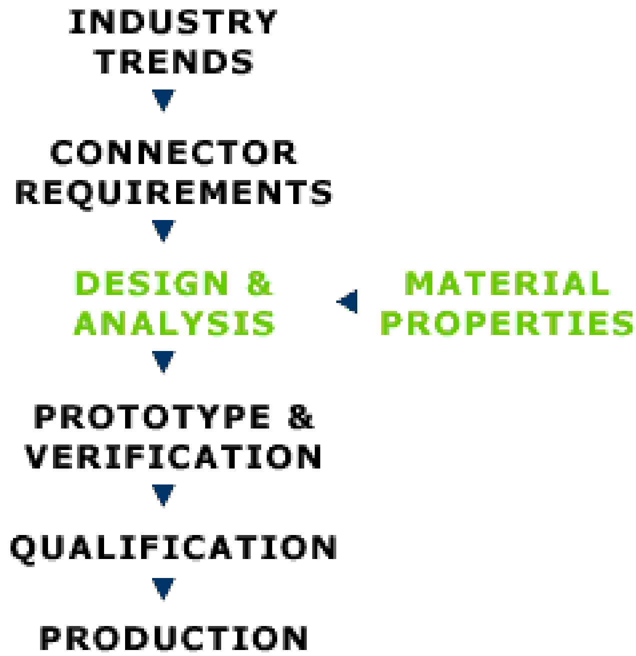
Design Guide - Table of Contents

DESIGN process



The design process involves a number of steps. Industry trends drive and dictate connector requirements. From these requirements, one must isolate the critical design factors and identify the overall class of alloy needed. After determining this, the designer is then in a position to specify the material characteristics that will most closely meet the application's overall performance, manufacturing, and cost requirements. A design review follows the detailed design and analysis step to ensure the achievement of requirements. Prototypes verify the final design. A qualification then certifies production level hardware. The qualification is a short term test to simulate long term performance. Once achieved, a connector is ready for the manufacturing challenges of production.

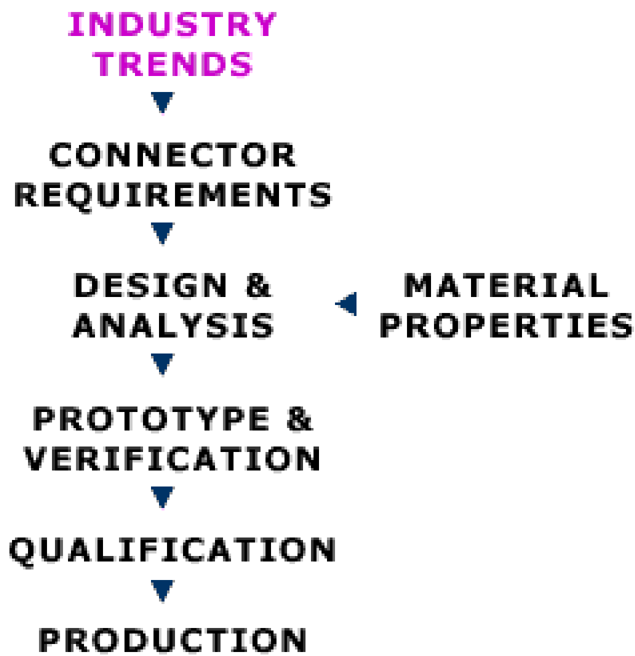
The design flowchart (right) illustrates the iterative process of connector design. We will consider each of the design factors and the material properties dictating connector performance. Considering this analysis, we will examine the specific properties that the designer must assess in each instance.



Section IX -- Applications includes a design example using the detail design flowchart (below).

INDUSTRY trends

In applications spanning the aerospace, automotive, computer, electronics, medical and telecommunications industries, material selection has emerged as the most critical task facing the connector designer today. Within these industries,
a number of trends have emerged that drive connector requirements.



Connector Requirement Drivers

Industry trends can be both technology and market driven. Examples of technology driven trends are miniaturization, higher pin counts, faster operating speeds, higher operating temperature and so forth. Market driven trends include lower price and shorter development cycles. The following list contains examples of both.

Technology Driven:

- **Miniaturization** -- Decreased volume for packaging dictates smaller centerline spacing, tighter tolerances and lower profiles that drive the need for smaller contacts and thinner strip material.

- **Lower normal force** -- Due to the limited deflections available in many new connector designs, and the desire for lowered engagement forces the contact normal forces are being lowered while still requiring equivalent reliability.

- **Higher pin counts** -- Higher levels of integration have increased the density of connectors up to and exceeding 100 contacts per inch and greater than 1000 contacts per connector.

- **Faster operating speeds** -- In order to operate at higher speeds, connectors require minimized signal path length and matched impedance.

- **Higher operating temperatures** -- Increased power requirements and harsher operating environments drive higher operating temperatures as electronics usage penetrates more industries.

- **Surface mount soldering** -- The connector supplies more mechanical support for the solder joint as the percentage of surface mount components is increasing per circuit board.

- **Less conservative designs** -- The greater predictive ability through the use of Finite Element Modeling Analysis is allowing designers to decrease the design safety factor with more confidence.

Market Driven:

- **Shorter development cycles --** The marketplace requires new products more quickly requiring shorter product development cycles. Shorter equipment life cycles also drive shorter development cycles.

- **Lower price --** Industry competitiveness is forcing the price of the final product lower thereby driving the cost of components such as connectors lower.

- **Greater durability --** Some connector applications require up to 10,000 insertion cycles in their lifetime.

In many connector applications, the reconciliation of such diverse performance, manufacturing, quality and cost parameters prove to be a function of the contact material. In such instances, the success of connector design hinges on the designer's ability to specify the contact material providing optimum performance, ease of manufacturing and cost effectiveness.

Technical Exchange

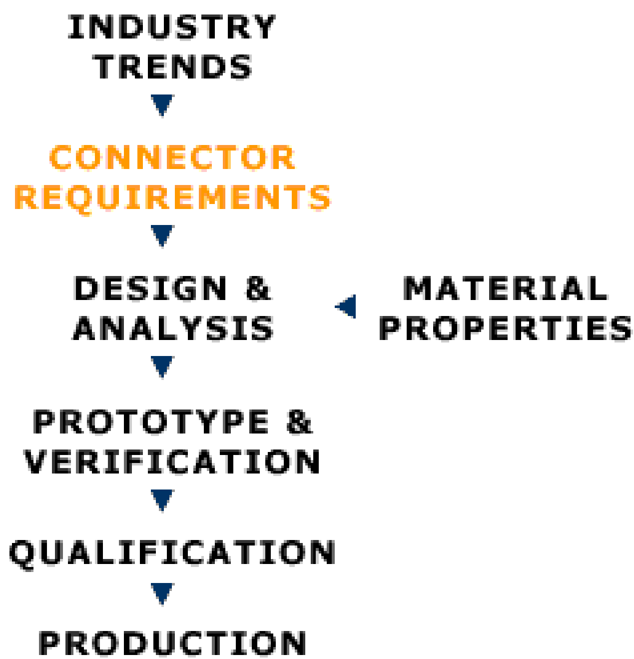
Section I: Design Process

Section III: Connector Requirements

Design Guide - Table of Contents

CONNECTOR requirements

The applications for high performance copper alloys encompass the full range of electrical-electronic connectors and interconnections. A connector must provide mechanical and electrical contact between two elements of an electronic system without unacceptable signal distortion or power loss. Depending on the requirements of a given application, either performance or manufacturing considerations will assume primary importance. However, it is the total combination of properties that ultimately dictates alloy selection.



Connector requirements break down into six distinct categories:

- Mechanical
- Electrical
- System
- Materials
- Process
- Environment

A glossary format defines the requirements.

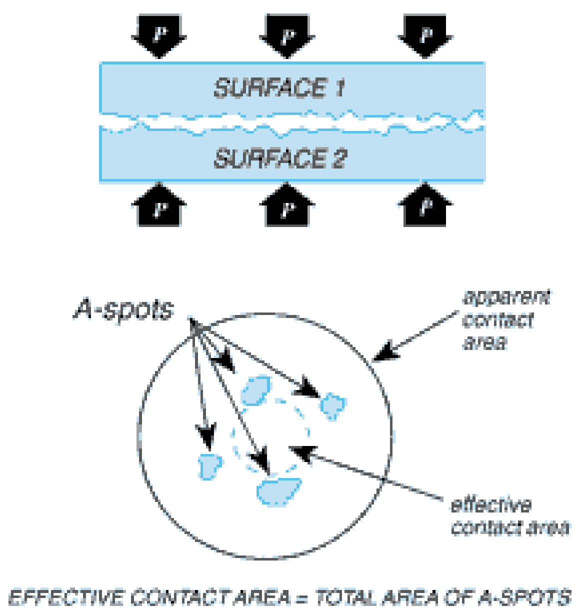
CONNECTOR requirements

Mechanical

Contact Theory

In order to understand the mechanical requirements of a connector system, one must understand how contact is made. Contact theory states that real surfaces are not perfectly smooth but consist of high regions (asperities) and low regions. Local regions of metal-to-metal contact are made when two conductive surfaces mate under sufficient load. Contact regions are where asperities from both surfaces touch, also known as A-spots (Figure 1). The number, density, and size of these A-spots vary. Their characteristics depend on the load applied, surface hardness, surface geometry, and the physical characteristics

FIGURE 1: CONTACT THEORY



of oxide or contaminant films present on the surfaces. The sum of A-spot areas is the effective contact area.

Contact (normal) force

Contact force, P, is the load required to keep two surfaces in contact. The force is perpendicular to the two surfaces, hence its other, name normal force. Maintaining a constant normal force is a direct indicator of the ability of a contact to maintain electrical integrity. A sufficiently large spring force (normal force) establishes the gas-tight interface between contact surfaces thus preventing corrosive contaminants from penetrating or forming between interfaces causing electrical instability. Section IV -- Material Properties discusses this critical property of connector design in greater depth.

Contact geometry

FIGURE 2: CONTACT GEOMETRY

High contact stress geometries aid in maximizing the effective contact area for a given load condition. This contact stress is the **Hertz** stress. Use the following assumptions when calculating Hertz stress.

1. Smooth surfaces in contact, a point will produce infinite stress

2. Contact area small compared to surfaces in contact

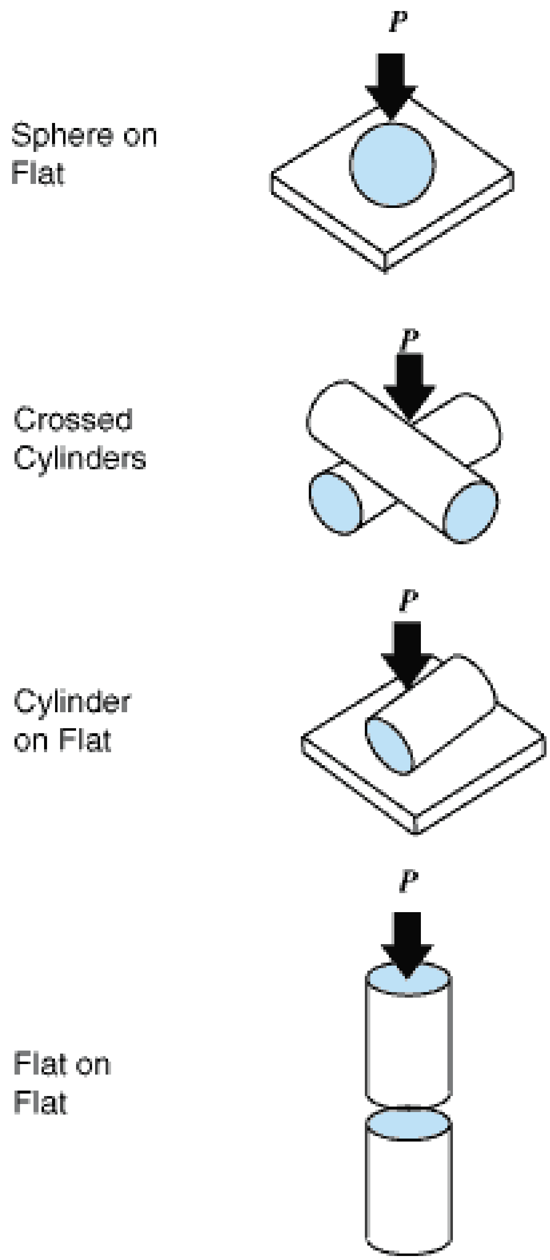
3. Elastic deformation

4. No friction

Preferred geometries in order of decreasing contact (Hertz) stress are sphere on flat, crossed cylinders, cylinder on flat and lastly flat on flat (Figure 2).

Insertion & Extraction forces

These are the forces required to mate and unmate two connectors. Do not confuse these forces with contact force. The insertion and extraction forces are proportional to the normal force and the coefficient of friction. Wear concerns, contact force, number of contact points, coefficient of friction, lead-in angle of the mating part and design requirements determine the allowable number of **insertion cycles**. Ergonomic issues during mating and assembly determine the **total mating force**. Connector mating forces of more than 15 lbs (66.6 N) often require mechanical aids. **Lubrication** lowers the insertion force and inhibits oxidation and corrosion. Non-sulfur containing lubricants are a requirement. The high temperature stability of the lubricant is also a consideration.



[Technical Exchange]

[Section III: Connector Requirements]

[Section III: Connector Requirements Electrical]

[Design Guide - Table of Contents]

CONNECTOR requirements

Electrical

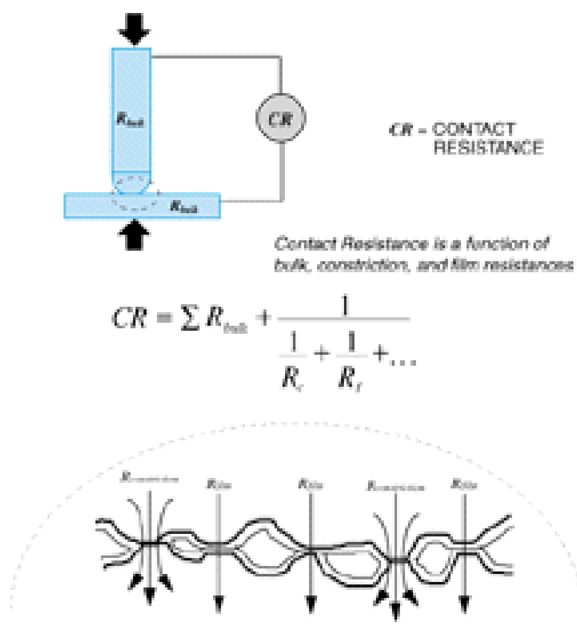
Connector resistance

The contact resistance of the separable or non-separable interfaces and the bulk resistance of the contact spring comprise the total connector resistance.

Contact resistance

Contact resistance is the electrical resistance of the interface between the two surfaces in contact. It is influenced by normal force, geometry and physical properties of the contacting surfaces. Contact resistancefurther breaks down into **constriction resistance** and **film resistance** (Figure 3).

FIGURE 3: CONTACT RESISTANCE



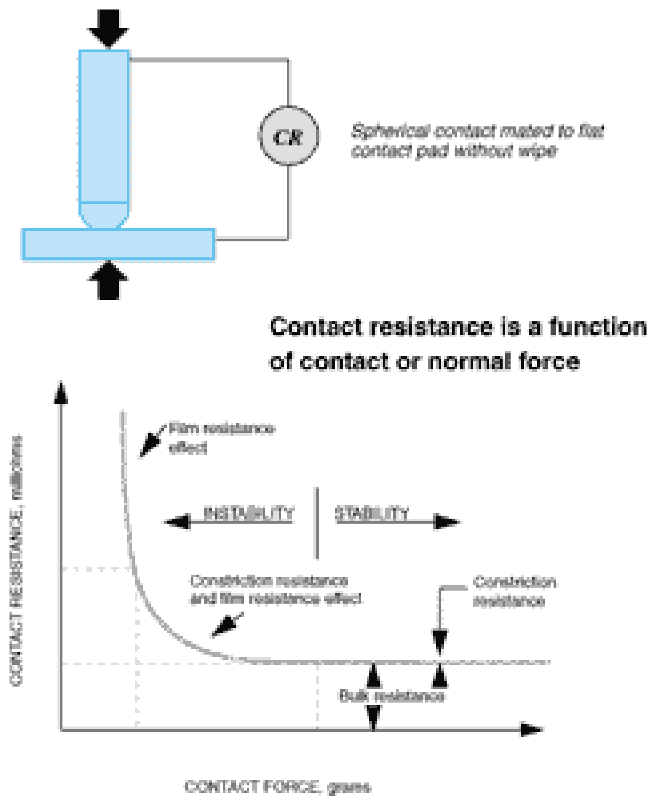
$$CR = \sum R_{bulk} + \cfrac{1}{\frac{1}{R_c} + \frac{1}{R_f} + \ldots}$$

Contact resistance is independent of contact size, and is dominated by the constriction resistance of tiny areas or A-spots. The film resistance is due to thin layers (as low as 20 angstroms) of insulating material between the contacts, caused by oxidation of the contact material or other contamination. These thin films conduct electrons by means of the tunneling effect. Both constriction and film resistance depend on the normal force and hardness of the contacting materials.

Figure 4 shows the relationship between contact force and contact resistance. The magnitude of the separable contact interface resistance is a few milliohms.

As the force increases, the asperities deform, bringing the surfaces closer together and increasing the number of the A spots.

FIGURE 4: CONTACT RESISTANCE VS. CONTACT FORCE



Bulk resistance

The contact spring bulk resistance is dependent upon the conductivity (resistivity) of the base material and its geometry. The magnitude of the spring bulk resistance is a few to tens of milliohms.

Power Properties

Current Capacity -- The maximum current allowed for a given temperature rise. Higher conductivity base material allows greater current flow with lower temperature rise. The current capacity of a connector is dependent on the contact material, geometry and normal force.

Signal Properties

One of the functions of a connector is to maintain electrical contact without unacceptable signal distortion. Signal properties are important for low current signals. A listing of a few signal properties appears below.

Signal to ground ratio -- The ratio of signal pins to ground pins in a connector. This ratio is useful in determining connector "noise."

Capacitance -- This is energy stored in an electric field between two charged objects. It is a means of coupling between signal conductors, or between signal and ground. A change in the voltage (potential) between the two components induces a current in the victim line, creating electrical noise.

Impedance -- The ratio of voltage to current of an electrical signal propagating through a curcuit component. It consists of energy lost through resistance, and energy stored by capacitance and inductance.

Inductance -- Energy stored in a manetic field generated by the current looping through an electrical circuit. A change in this current induces a voltage in nearby conductors, generating electrical noise.

Delay -- The signal delay caused by the connector capacitance or the propagation delay. Reduced connector length reduces the propagation delay.

Cross talk (coupled noise) -- Signals from one line leaking into another conductor because of capacitance or inductive coupling or both.

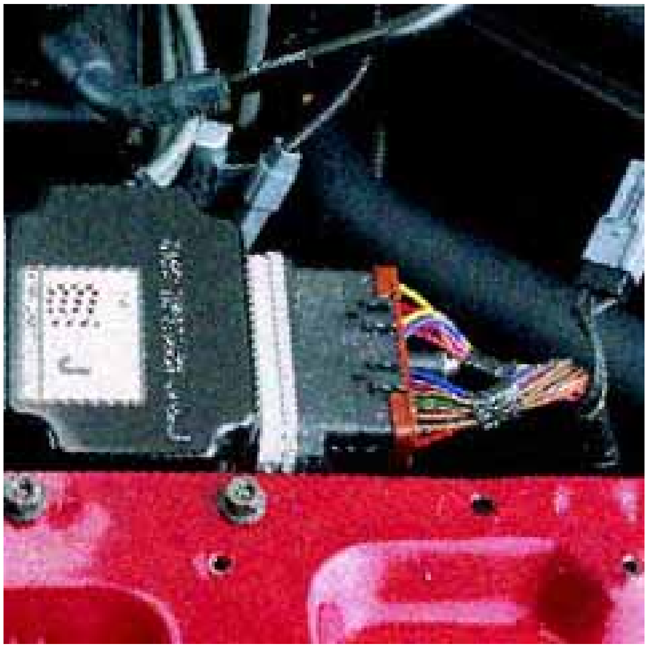
Insulation resistance -- The resistance to current flow thrrough an insulator when applying a potential. The measured resistance value is megohms on the housing material or wire insulation.

Dielectric strength (withstanding voltage) -- The highest potential difference (voltage) that an insulating material of given thickness can withstand for a specified time without the occurrence of electrical breakdown through its bulk. The measured voltage value is on housing materials and wire insulation.

CONNECTOR requirements

System

Reliability



The reliability of a system is dependent on the failure rate of its components. Reliability can be measured by the proportion of items not failing from a group, or the probability that an item will function without failure, over a stated time period starting at time zero. Failure rates define reliability. The failure rate is the rate at which devices from a given population can (or were found to) fail as a function of time (for example, %/1000 hours of operation). Connectors can fail due to plug dependent mechanisms, wear-out mechanisms or corrosion mechanisms. In this case failure is defined as the percentage of the test population exceeding a specified change in contact resistance (typically 10 milliohms). The total system life or **power-on-hours (POH)** and the **on/off cycles** or number of times that a product powers on and off are important factors determining system reliability. A wiping action with multiple contact points improves a connector's reliability. **Wipe** is a requirement to break through oxide films and displace contaminants during insertion. **Redundancy** decreases the probability of contamination affecting all contact points simultaneously. Stress (environmental) tests predict the product's performance in the field under the anticipated operating conditions.

Cost

Cost analysis determines the overall cost of the connector versus an alternate solution or, the cost of a connector using various base materials. The connector cost analysis also evaluates the various base materials versus the performance of the material. Section VIII - Production contains additional comments on cost.

Package envelope

The system determines the overall size allowed for the connector (length, width, height) in the package. As the volume available for connectors decreases, the **grid** or contact spacing per inch decreases, requiring the material to become thinner and stronger. The tolerances required on the connectors also tighten. **Guidance features** prevent misalignment and overstressing of the contacts during mating. **Positive retention** prevents disconnection instead of relying on the contacts to provide all the retention.

Standards and specifications

Customer and industry driven specifications or standards determine many of the functional requirements of a connector. In addition, they specify the stress tests for qualification of the connector.

Technical Exchange

Section III:
Connector Requirements
Electrical

Section III:
Connector Requirements
Materials

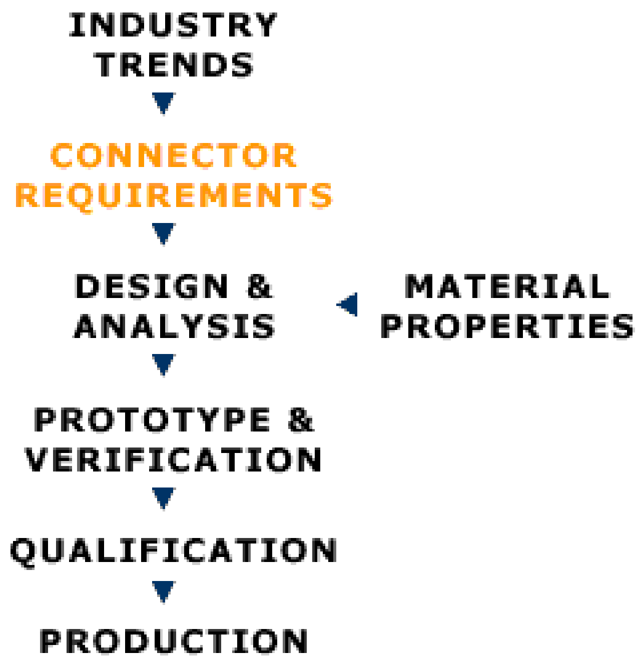
Design Guide -
Table of Contents

CONNECTOR requirements

Materials

Several properties are desirable in a connector material:

- Low contact and bulk electrical resistance to meet circuit requirements
- Corrosion resistance
- Low friction forces with good wear resistance for repeated reliable insertions
- Adequate spring characteristics
- Low cost



To meet these requirements, the contact surfaces consist of a hierarchy of metals. A nickel underlayer and a precious (Au, Pd) or non-precious (Sn) metal overplate coat the copper alloy base metal.

Base metal

These are typically high performance copper alloys containing a combination of good electrical conductivity and good mechanical spring and forming properties. Proper selection of the base materials considers the following:

- Conductivity -- minimize bulk resistance
- Ductility -- aid in forming the contact
- Yield strength -- maximize beam deflections in the elastic range
- Stress relaxation -- resist load relaxation with time at constant strain and elevated temperatures
- Hardness -- reduce wear of contact metallization

In later sections this guide deals with these considerations in detail.

Connector interface materials

The main purpose of interface materials is protection of the copper alloy base metal from corrosion. These materials are selected for nobility (resistance to environmental attack and adsorption of organic molecules), hardness (wear resistance) and ductility (to maximize contact area and resist cracking or spalling). Gold, palladium and its alloys, and tin and its alloys are common overplate choices. Nickel is the most common underplate.

Gold (Au)

Hard gold (cobalt or nickel hardened) is the most common precious metal overplate. Gold plates from acid cyanide solutions with deposits ranging from soft to hard, with bright finishes offering excellent corrosion resistance and good electrical properties. **Soft gold** is 24 carat or 99.99 percent minimum purity. Soft gold solders easily, but has very poor wear properties. Industrial **hard gold** is 99-99.8 percent gold alloyed with cobalt or nickel as the hardening agent and is quite durable, with ductile deposits. Gold overplate thicknesses of 10-30 microinches (0.25-0.8 microns) provide good wear, friction, electrical and corrosion properties. The two disadvantages of gold are that hard gold has reduced solderability, and that gold is expensive.

Palladium (Pd) and its alloys

Palladium and its alloys (e.g. palladium-nickel and palladium-cobalt) are usually overplated with a thin soft gold flash (<10 microinches or 0.25 microns). These alloys are comparable to gold in terms of corrosion resistance and contact resistance. Palladium and its alloys have a higher hardness and durability rating than gold alloys. However, these alloys are more sensitive to general corrosion than is gold.

Tin (Sn) and its alloys

This alloy system deposits coatings by electroplating as well as hot dipping. Two methods for hot dip tinning are: hot dipping with mechanical wiping for coating thicknesses between 30 and 80 microinches (0.8 and 2.0 microns) and hot dipping with air knife finishing for tin coatings thicker than 60 microinches (1.5 microns). The thickness limit of electroplated tin coating is 40-120 microinches (1-3 microns). Reflow tin is tin electroplate reflow heated in a furnace after plating to smooth the coating and increase grain size. The main advantages of hot dip tinning are solderability improvement, adhesion to strip, bendability and lower production costs. Pure tin plating is subject to "whiskering" that can lead to electrical shorting. To avoid "whiskering" add a minimum of 7% weight percentage of lead (Pb) or reflow after plating.

Nickel (Ni)

The nickel underplate layer serves several purposes:

- Nickel acts as a barrier to copper diffusion through gold, which in turn allows usage of a thinner layer of gold. The nickel underplate reduces porosity through to the copper alloy base metal maintaining a corrosion free surface.

- Nickel is harder than gold and therefore increases the durability of gold by providing a hard substrate foundation improving wear characteristics.

- Precious metal plating baths are sufficiently acidic or basic so as to dissolve small amounts of copper prior to initiation of plating. The lifetime of the precious metal plating solution increases since this does not occur with nickel.

Electroplated nickel can vary widely in its properties. Hardness, ductility, stress and tensile strength are functions of the plating solution. Three typical nickel plating baths are sulfamate, fluoborate and pyrophosphate. Typical Ni underplate thickness is 50-100 microinches (1.25-2.5 microns).

Plating porosity

Porosity is the presence of pores (small holes) in the plating. Porosity is dependent on plating thickness and parameters as well as substrate defects. Pores may be sites at which corrosion can occur. Corrosion products or films arise from an interaction between the non-noble portions of the contact member and the environment, through pores in noble platings.

Plating processes

The most common deposition processes are electroplating, electroless plating, hot dipping and cladding.

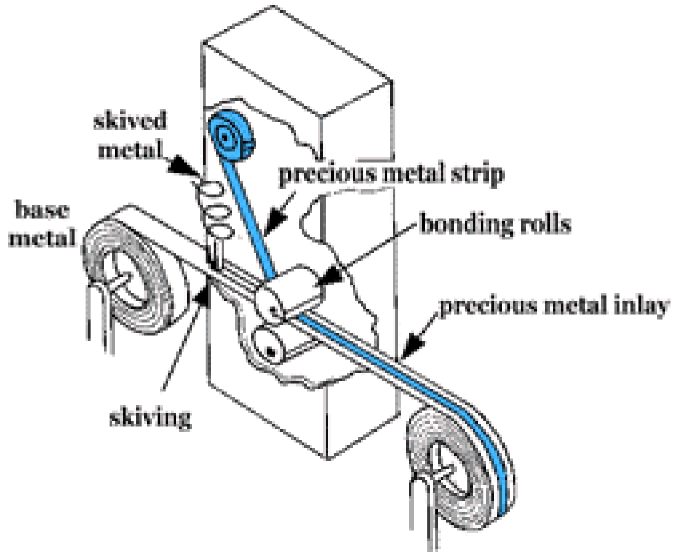
Electroplating is the deposition of an adherent metallic coating onto a conductive object placed into an electrolytic bath composed of a solution of the metal plating salt. Using the terminal as the anode, a direct (DC) current passes through the plating solution affecting transfer of metal ions onto the cathodic plating surface. Electroplating technology allows the selective deposition of plating only in the required functional areas.

Electroless plating is metal deposition, usually in an aqueous medium, that proceeds by an exchange reaction between metal complexes in the solution and the particular coated metal. The reaction is autocatalytic and does not require externally applied electric current.

Hot Dipping is the oldest method of metal coating. The process consists of dipping parts into molten metal. Use this method only if the metal to be coated forms an intermetallic alloy with the coating. In addition, the melting point of the coating must be considerably below that of the metal to be coated, for example tin on copper. It is important that the contact surface is pure tin and not the tin intermetallic. The advantage of hot dipping is the relative simplicity and the high output rate. A drawback of the hot-dip method is that it is difficult to control the thickness of the coating. Hot dipped tin finishes are not susceptible to "whiskering."

Cladding is a thin layer of a metal mechanically bonded to a base metal, usually by heating and rolling (Figure 5). There are two types of cladding: stripe-inlay cladding and overlay cladding. Stripe-inlay cladding imbeds a stripe, or stripes, of precious metal in a base metal. The top surface of the inlay is flush with the base metal surface. Two materials are permanently bonded together by rolling under high pressure and temperature in a bonding mill. Overlay cladding provides a layer, or a stripe, of coating on a metallic surface. Cladding of solder to the metal may be done by pressure (bonding) or by re-flowing the melted solder onto the base metal surface. Claddings are not subject to porosity since the inlay metals are wrought. The combination of precious metal and tin or solder cladding on the same strip metal may offer manufacturing advantages.

FIGURE 5: STRIP- INLAY CLADDING PROCESS



Housing material

Polymer based thermoplastics isolate, locate and support contacts, enhance alignment and provide environmental protection for connectors. The material chosen should be compatible with connector processing such as soldering. The critical property of thermoplastic during soldering is the Heat Deflection Temperature. Other desirable properties are dimensional stability, low warpage, moisture resistance and ability to be moled in thin sections.

CONNECTOR requirements

Attachment Process

Solder process

A connector mechanically and electrically connects to a printed circuit board or other substrate via a solder process. Selection of the best solder process depends on the number, type and complexity of the joints. The following reasons demonstrate why rapid heating and cooling is the recommendation for all cases:

- High temperatures can cause oxidation of the beryllium copper substrate
- Fluxes will degrade during prolonged heating.
- Overheating may cause metallurgical changes in beryllium copper.
- Excessive heating causes intermetallic compound formation at the solder-substrate interface, leading to a loss in bond strength.

The various types of solder processes include manual, wave, vapor phase reflow and infra-red reflow. The following list provides processes in order of increased process temperatures.

Manual soldering or hand soldering uses a soldering iron in low volume operations where rapid heating rates are critical. Dip soldering of prefluxed assemblies requires immersion in a solder pot from a few seconds to several minutes.

Wave solder application and reflow directs a jet of liquid solder at the connection of the metallic parts. The technique usually involves processing steps to apply flux and remove excess solder. Elevated temperature limits exposure times to a few seconds.

Intrusive reflow uses solder paste in the surface mount process to hold a limited number of odd-form through-hole components in place during reflow. The leads of the surface mount components insert into the solder paste, and through hole leads insert through the paste to hold the component in place during reflow soldering.

Vapor phase reflow uses a vapor to heat the solder joint. Vapor phase soldering offers advantages for selective or inaccessible joining operations, since it provides precise temperature control in a contamination-free environment. Solder is a paste or pre-form, and the elevated temperature exposure time varies from 10-180 seconds.

IR (Infra-Red) reflow consists of melting solder by infrared heat. Normally a circuit board having prepositioned and tin-lead plated connectors is transported through an IR reflow furnace.

Mechanical Attachment

Most of the mechanical methods of attaching components to printed circuit boards or wire replace the solder process. Mechanical connections tend to have higher normal force requirements than separable connections.

Compliant pin (Press-fit)

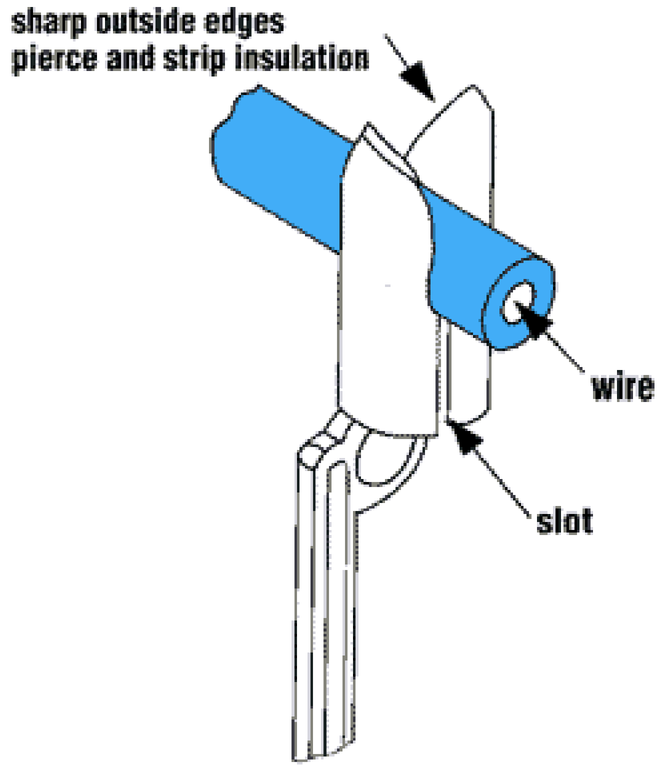
A mechanical connection between a compliant pin and plated-through-hole (PTH) is a means of decreasing the process steps in printed circuit assembly. The technology involves pushing a pin or post through a plated-through-hole. The compliant pin contains a section that deforms, conforming to the PTH. This process eliminates the solder process step as well as the pre and post cleaning treatments. A number of material properties are important for this application. The compliant energy of the pin section is important in predicting the reliability of the joint relating to the material's spring properties. The formability of the compliant contact section is also critical. In addition, strength is important when inserting the pins into PC boards to prevent buckling.

Insulation displacement (IDC)

FIGURE 6: INSULATION DISPLACEMENT CONNECTOR

IDC is a method to mass terminate ribbon cable to contacts. Here the contact pierces the cable insulation and makes intimate electrical contact with the conductor in a ribbon cable (Figure 6). The yield strength of the material is critical to prevent overstressing during insertion of the conductor and insulation.

Stress relaxation resistance over time is important since the normal force is the sole means of maintaining electrical contact. The hardness of the contact edges to penetrate the wire insulation is also a critical factor. Insulation displacement connectors offer a one-piece connector housing with preloaded terminals for high volume manufacturing processes.



Crimps

The crimp is a method to terminate an individual wire conductor to a contact. Cold welding provides the electrical and mechanical integrity of crimps. The cold welding results from the deformation of the contact and conductors producing microwelds at the film free surfaces. Several criteria are critical for a gas tight crimp. These are formability and springback as well as strength of the material to deform the wire during crimping. The amount of conductor deformation is critical in producing an effective crimp. A second crimp over the conductor's insulation forms a strain relief.

Compression contacts

This method is a separable contact system. Compression type contacts are Z-axis non-wiping connectors that contact two planar substrates. A continuously applied force (such as a spring, wire or elastomer rubber) maintains electrical contact. Planarity of the two substrates is a critical issue.

Compatibility

Temperature and chemical in-process -- Connectors require compatibility with acids and weak bases, solvents and miscellaneous chemicals (oxidizing agents, water) that would be part of the soldering process.

Automated handling -- In a high volume manufacturing environment, smaller connectors are packaged in standard tape- and-reel format, whereas longer connectors are packaged in tubes, trays or non-standard tapes. Robotic handling requires special locating features.

Pin-in-hole or surface mount -- Components attach to a printed circuit board either by inserting a pin in a plated-through-hole in the PC board or by soldering a lead to a pad using surface mount techniques. The surface mount techniques rely on solder for strength. Some connectors are not conducive to surface mount soldering because of their size, weight, required insertion force and lack of flat surfaces, which lend themselves to pickup by vacuum nozzles. The higher densities required of newer connectors have helped shrink their size and weight to help address this concern.

CONNECTOR requirements

Environment

Operating class

The more common electronic applications are: automotive (passenger compartment and underhood), consumer, medical, telecommunications, aircraft and space, military (avionics, weapon systems, communications), computer (mainframe, mid-range, PC, workstation, supercomputer), process control (heavy industry, light industry), test and burn-in. Table 1 provides typical operating environments.

TABLE 1 - OPERATING ENVIRONMENTS

	T min		T max		Years of
Use Category	**(°F)**	**(°C)**	**(°F)**	**(°C)**	**Service**
Consumer	+32	0	140	+60	1-3
Computers	+59	+15	140	+60	≈5
Telecom	-40	-40	185	+85	7-20
Commercial Aircraft	-67	-55	203	+95	≈20
Industrial & Automotive Passenger Compartment	-67	-55	203	+95	≈10
Military Ground & Ship	-67	-55	203	+95	≈5
Space LEO & GEO	-40	-40	185	+85	5-20
Military Avionics	-67	-55	203	+95	≈10
Automotive Underhood	-67	-55	347	+175	≈10

Subclasses

Each operating class defines ranges of the following additional parameters.

Psychrometric class -- Temperature and humidity ranges.

Gaseous class -- Concentration ranges for corrosive gases. The gases and gas families are: S_x, (Total Reduced Sulfur) that includes all of the sulfur in elemental sulfur vapor or in any sulfur compounds that are sulfiding gases (H_2S), Cl_x, (Acidic chlorine gases) that includes gaseous chlorine (Cl_2), and the chlorine contained in gaseous hydrogen chloride (HCl), SO_2, (Sulfur dioxide), NO_2, (Nitrogen dioxide) and O_3, (Ozone) or total oxidant that includes ozone and defines all substances other than nitrogen dioxide that oxidize iodide ions to iodine under neutral pH conditions.

Particulate class -- Concentration ranges for atmospheric particulates.

Shipping and storage class -- All products, regardless of their intended application, must be capable of withstanding exposure to the atmospheric environment during periods of shipment and storage prior to actual installation with no degradation. This typically includes thermal shock and condensation, but not rain. Excessively long storage times permit films to form on some metal surfaces.

Vibration class -- The class includes operational, shipping and relocation vibration.

Shock class -- Requirements include impact to the product during shipping and handling.

Technical Exchange

Section III:
Connector Requirements
Attachment Process

Section IV:
Material Properties

Design Guide -
Table of Contents

FIGURE 5: STRIP IN-LAY CLADDING PROCESS

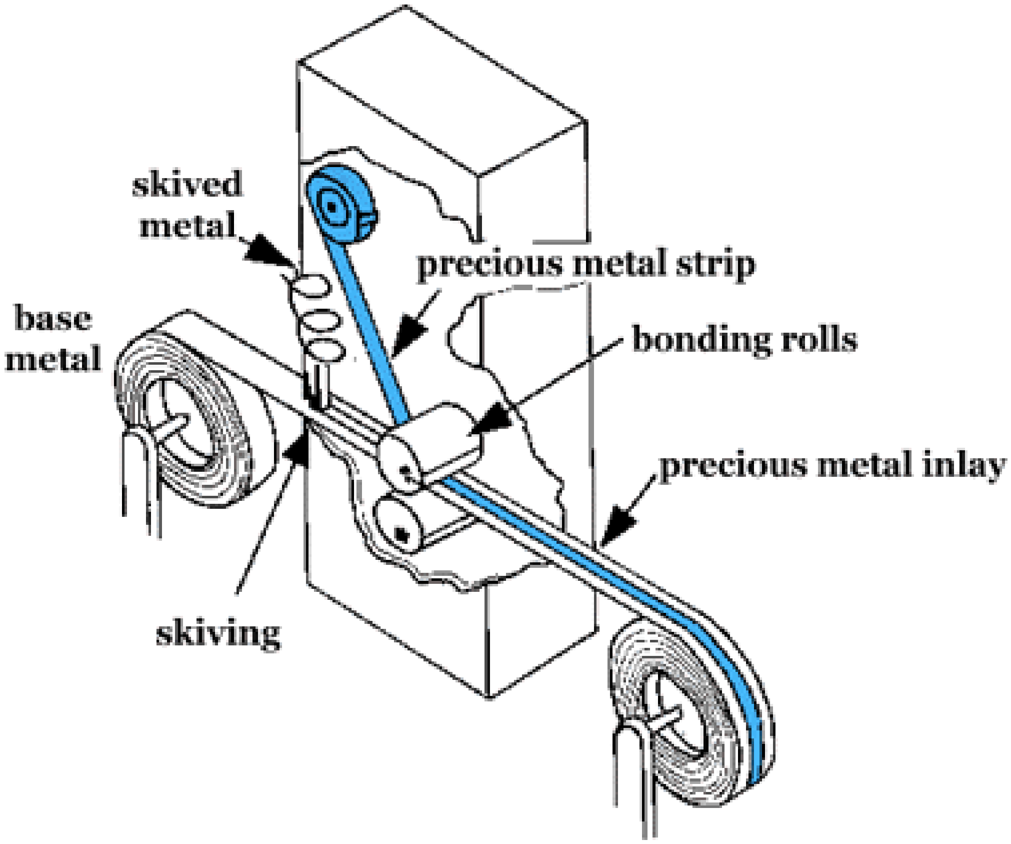
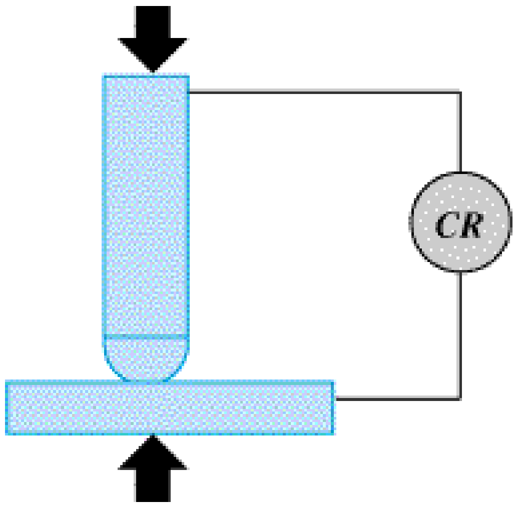


FIGURE 4: CONTACT RESISTANCE VS. CONTACT FORCE



Contact resistance is a function of contact or normal force

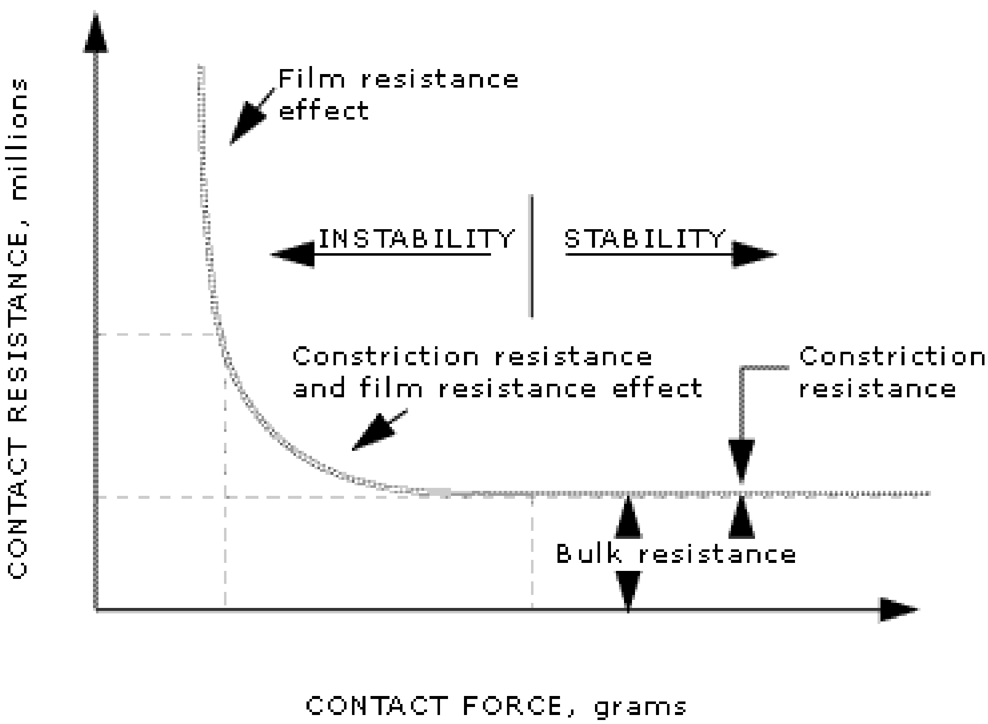


FIGURE 6: INSULATION DISPLACEMENT CONNECTOR

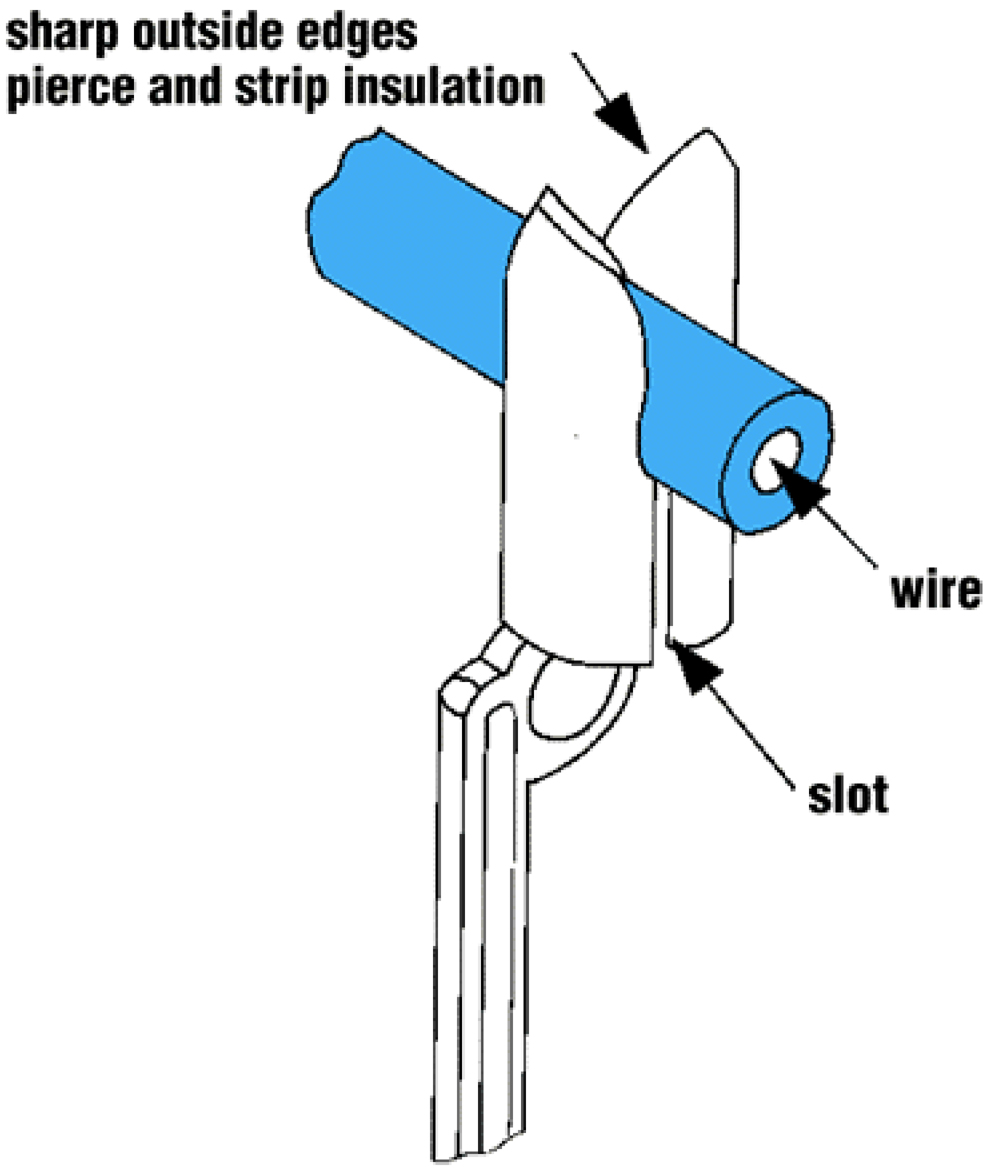


Figure 5 Figure 7

FIGURE 1: CONTACT THEORY

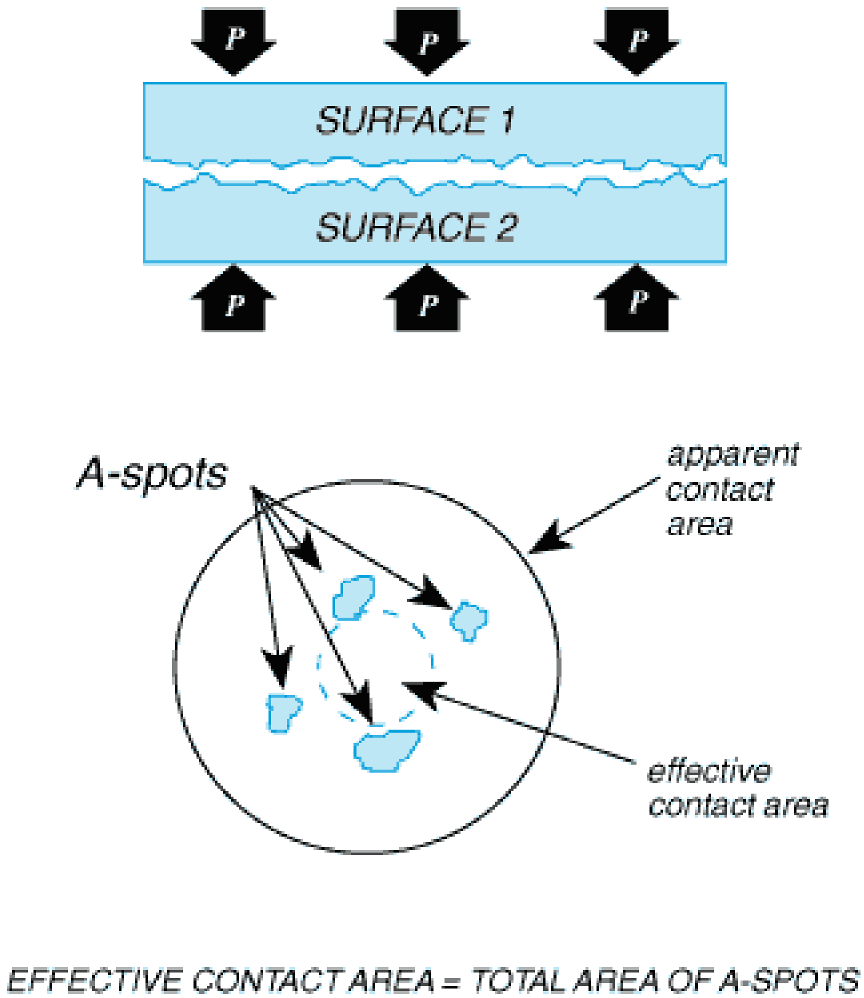


Figure 47 Figure 2

MATERIAL properties

Design optimization is dependent upon selecting the correct material to achieve the required criteria. Table 2 identifies the critical design requirements and the material properties that influence them.

INDUSTRY TRENDS
▼
CONNECTOR REQUIREMENTS
▼
DESIGN & ANALYSIS ◄ MATERIAL PROPERTIES
▼
PROTOTYPE & VERIFICATION
▼
QUALIFICATION
▼
PRODUCTION

TABLE 2 -
DESIGN REQUIREMENTS VS. MATERIAL PROPERTIES

Design Requirements	**Material Property**
Normal Force	Modulus of Elasticity Material Dimensions & Tolerances
Insertion Cycles or Durability	Resistance to Permanent Set Fatigue (Low Cycle, R 5 0) Contact Finish
Load / Deflection Limits Design Stress	Yield Strength, Modulus of Elasticity
Current Carrying Capacity	Conductivity (Electrical & Thermal) Stress Relaxation
Reliability	Stress Relaxation Contact Finish
Cost	Density

Table 3 - Copper Alloy Composition and Density

UNS Designation	Brush Alloy	Alloy Name	Chemical Composition (wt %), Cu Balance	Density (lb/in^3)	Density (g/cm^3)
C17200*	25	Copper Beryllium	1.8 Be, 0.2 Co	0.302**	8.36**
	190	Copper Beryllium	1.8 Be, 0.2 Co	0.302**	8.36**
	290	Copper Beryllium	1.8 Be, 0.2 Co	0.302**	8.36**
C17300*	M25	Copper Beryllium	1.8 Be, 0.2 C0, 0.2-0.6 Pb	0.302**	8.36**
C17510*	3	Copper Beryllium	1.7 Ni, 0.3 Be	0.319***	8.83***
C17410*	174	Copper Beryllium	0.3 Be, 0.5 Co	0.318	8.80
C17460*	60	Copper Beryllium	1.2 Ni, 0.3 Be	0.318	8.80
C19150*	1915	Leaded Nickel Copper	1.0 Ni, 0.8 Pb, 0.25 P	0.320	8.88
C19900*	199	Copper Titanium	3.2 Ti	0.314	8.70
C19400		Copper Iron	2.4 Fe, 0.1 Zn	0.317	8.78
C26000		Cartridge Brass	30 Zn	0.308	8.53
C51000		Phosphor Bronze A	5.0 Sn, 0.1P	0.320	8.86
C52100		Phosphor Bronze C	8.0 Sn, 0.1 P	0.318	8.80
C65400		Silicon Bronze	3.0 Si, 1.5 Sn, 0.1 Cr	0.309	8.55
C68800		Aluminum Brass	22.7 Zn, 3.4 Al, 0.4 Co	0.296	8.19
C72500		Cu-Ni-Sn	9.5 Ni, 2.3 Sn	0.321	8.89
C70250*		Cu-Ni-Si	3.0 Ni, 0.65 Si, 0.15 Mg	0.318	8.80
C72700*		Spinodal	9.0 Ni, 6.0 Sn, 0.1 Mn	0.321	8.89
C72900*		Spinodal	15.0 Ni, 8.0 Sn	0.323	8.95
N03360	360	Nickel Beryllium	2.0 Be, 0.5 Ti, Ni Balance	0.294	8.14

* = age hardenable materials

** = density before age hardening = 0.298 lb/in^3 (8.25 g/cm^3)

*** = density before age hardening = 0.316 lb/in^3 (8.75 g/cm^3)

Strengthening mechanisms

Structure plays an important role in the mechanical behavior of solids. Structure depends on chemical composition and then on processing. Such processing steps as hot and cold reduction, solution annealing and heat treatment all influence mechanical properties. Three strengthening mechanisms are solid solution hardening, work hardening and age hardening **(Figure 7).**

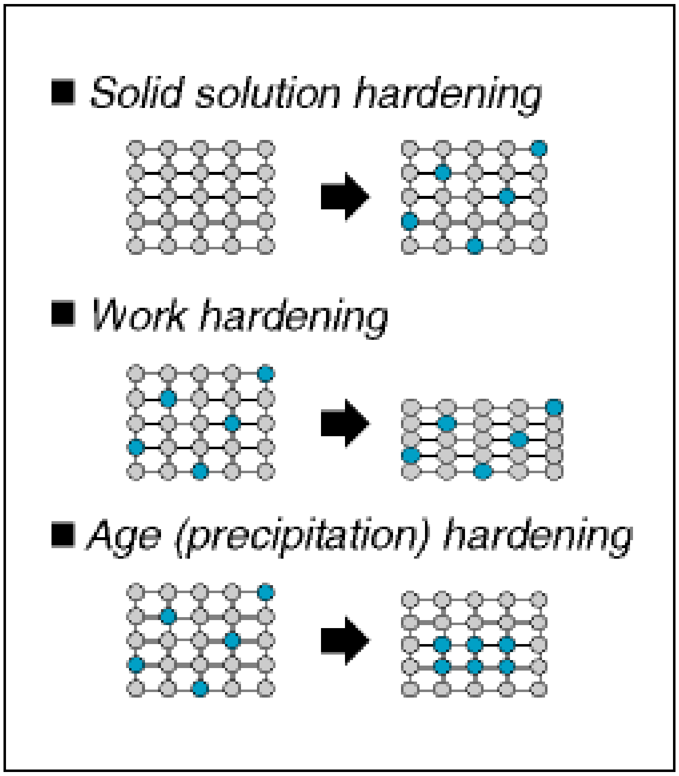
Solid solution hardening

The addition of other metallic elements increases strength by impeding dislocation motion. Dislocations are crystal imperfections. The effectiveness of the addition depends on the percentage present and the size difference. This is alloying.

Work hardening (cold work)

Mechanical deformation increases alloy strength. Stored energy as a result of the cold-work process is the strengthening mechanism. The major part of the stored energy is due to generation and

FIGURE 7: STRENGTHENING MECHANISMS



interaction of dislocations. The grains tend to become elongated in the deformation direction and take on a preferred crystallographic orientation or "texture." Work hardened alloys strengthen by varying amounts of deformation. Controlled mechanical operations that change the form or product cross-section and produce a strain hardened product at temperatures below the recrystallization temperature impart the deformation. Greater deformation increases alloy strength and typically decreases ductility. Controlled amounts of cold work of solution annealed alloys produce different properties. Table 4

Age (Precipitation) hardening

Heat treatment increases the strength of heat treatable alloys and is more effective than cold work, grain size reduction or solid-solution hardening. The alloy is first solutionized by heating into the single phase region, held there long enough to dissolve all existing soluble precipitate particles, and then rapidly quenched into the two phase region. The rapidity of the quench prevents formation of equilibrium precipitates and thus produces a super-saturated solid solution. On aging at or above room temperature, fine scale transition structures form. A variation of age hardening is **spinodal** hardening. The spinodal decomposition strengthening mechanism yields a rearrangement of atoms to form controlled compositional fluctuations instead of the discrete precipitates common to normal precipitation or age hardening.

Age hardening of beryllium copper involves the precipitation of a hard beryllide *-phase within the copper alloy matrix. The hard phase has a higher density than the matrix, and its formation at elevated temperature leads to a slight volume change during the aging cycle. The volume change is negative, which means that the density

TABLE 4 -
TEMPER DESIGNATION VALUES

Brush Designation	ASTM Designation	Description	Cold Rolled or Drawn Thickness Reduction (%)	
			STRIP	WIRE
A	TB00	Solution Annealed	0	0
1/4 H	TD01	Quarter Hard (work hardened)	11	21
1/2 H	TD02	Half Hard	21	37
3/4 H	TD03	Three-Quarter Hard	29	50
H	TD04	Hard	37	60
S	TD06	Spring	60	84
XS	TD08	Extra Spring	69	90
AT	TF00	Heat treated - age or precipitation hardened		
1/4 HT	TH01	(Standard heat treatment following work hardening & forming)		
1/2 HT	TH02			
3/4 HT	TH03			
HT	TH04			
AM	TM00	Mill hardened - no additional treatment needed		
1/4 HM	TM01			
1/2 HM	TM02			
3/4 HM	TM03			
HM	TM04			

increases. For the high strength beryllium copper alloys (25, M25, 165) the volume change is about -0.6%. Correspondingly, the linear dimensional change is -0.2%. The high conductivity beryllium copper alloys (3,10) have a negligible volume change during age hardening due to their low beryllium content.

SHM	TM05
XHM	TM06
XHMS	TM08

Heat treated

Alloys strengthened by thermal treatment after stamping. Not all alloys are heat treatable. Solution annealing, cold working, and precipitation heat treating alloys produces heat treated (HT type) tempers. As an example, cold working Alloy 25 strip to 1/2 H, stamping and then heat treating results in 1/2 HT properties.

Mill hardened

Alloys heat treated by the supplier. Mill hard (HM type) tempers of heat treated materials as supplied by the mill result from combinations of cold work and precipitation heat treatment. Mill hard material requires no additional heat treatment after stamping.

For additional information on heat treating beryllium copper refer to Section VIII -- Production.

Temper designation (ASTM B 601)

Temper is the metallurgical structure and properties of an alloy resulting from thermal and mechanical processing treatments. The strength of an alloy is adjustable within a wide range to meet part specifications. This variation in strength is temper. Specifically, the supplier obtains different tempers by either varying the amount of deformation in the strip rolling or wire drawing process or by varying the processing parameters of heat treatable alloys. Table 4 provides a description of the common alloy tempers.

Table 2 - Design Requirements vs. Material Properties

Design Requirements	Material Property
Normal Force	Modulus of Elasticity Material Dimensions & Tolerances
Insertion Cycles or Durability	Resistance to Permanent Set Fatigue (Low Cycle, R 5 0) Contact Finish
Load / Deflection Limits DesignStress	Yield Strength, Modulus of Elasticity
Current Carrying Capacity	Conductivity (Electrical & Thermal) Stress Relaxation
Reliability	Stress Relaxation Contact Finish
Cost	Density
Fabrication / Size	Formability Machinability Solderability

FIGURE 7: STRENGTHENING MECHANISMS

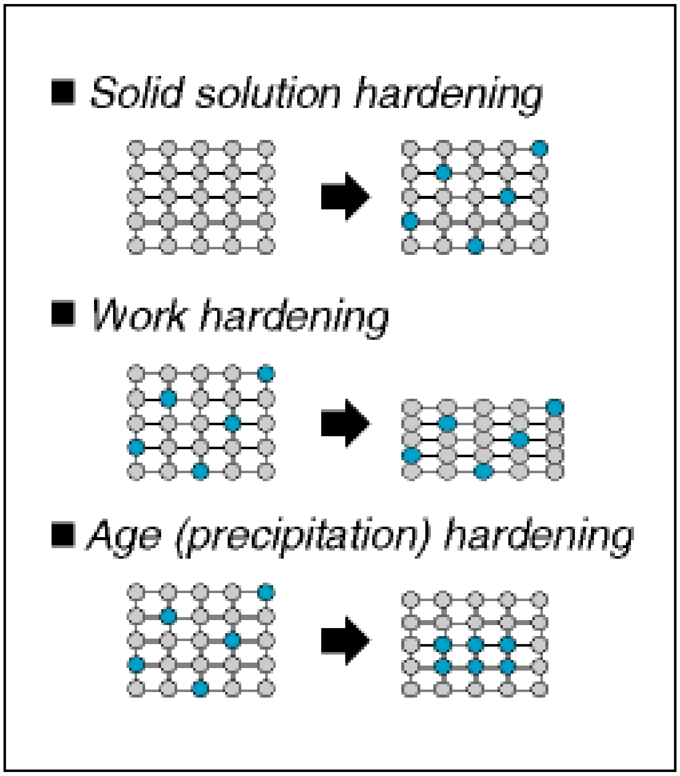


Figure 6 Figure 8

MATERIAL properties

Mechanical properties

Mechanical properties such as elastic modulus and yield strength are the basis for material selection in a variety of applications. In applications, materials are seldom, if ever, subjected to a single, steady deformation without the presence of other adverse factors such as environment and temperature. A thorough understanding of mechanical properties and tests employed to determine such properties, as well as effect of adverse conditions over long periods of time, is extremely important. For this reason, Brush Wellman offers Design & Technical Service to its customers. Section V -- Design Review lists additional information on the service. This service is available at no cost by contacting the toll-free number **1-800-375-4205**.

INDUSTRY TRENDS
▼
CONNECTOR REQUIREMENTS
▼
DESIGN & ANALYSIS ◄ MATERIAL PROPERTIES
▼
PROTOTYPE & VERIFICATION
▼
QUALIFICATION
▼
PRODUCTION

Primary

A basic understanding of load, deflection, and stress starts with a simple uniaxial tensile test, shown in Figure 8.

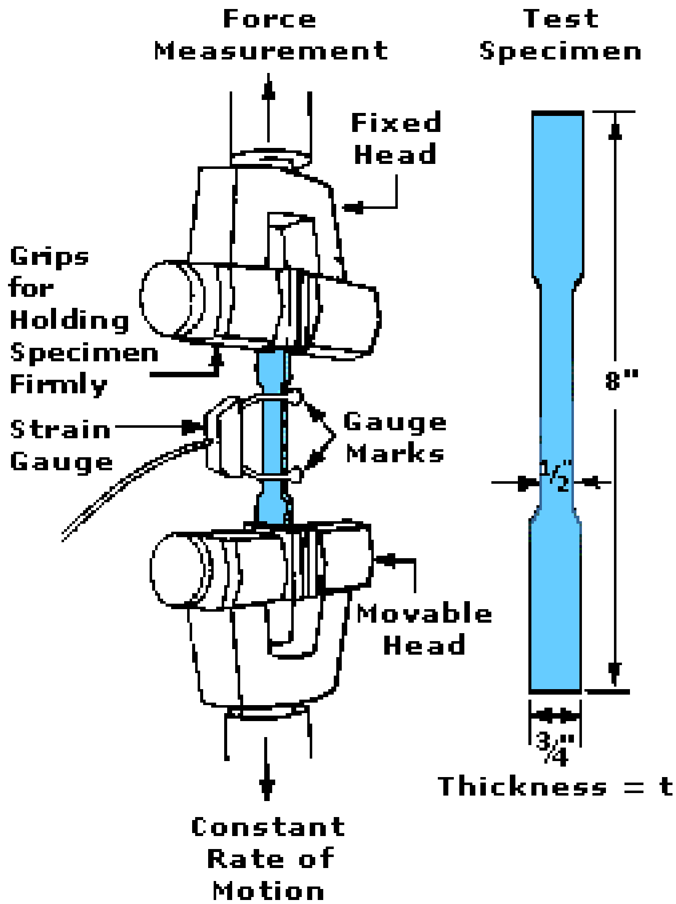


FIGURE 8: UNIXIAL TENSILE TEST

Stress (normal)

Direct stress is the ratio of applied load to the original cross-sectional area in a simple tension test expressed in pounds per square inch (psi) or kg/mm^2.

$$\textit{Stress},\ \sigma = \frac{\textit{Load}}{\textit{Area}} = \frac{L}{A}$$

Strain (normal)

FIGURE 9: SIMPLE TENSION LOAD

A measure of the deformation of the material that is dimensionless. Figure 9.

$$\textit{Strain},\ \epsilon = \frac{\textit{change in length}}{\textit{original length}} = \frac{\Delta L}{L}$$

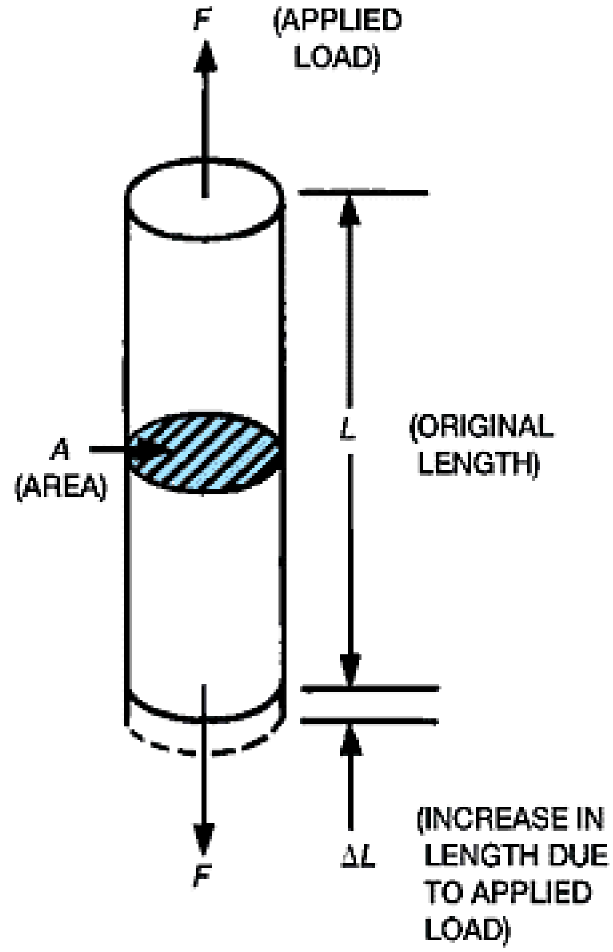
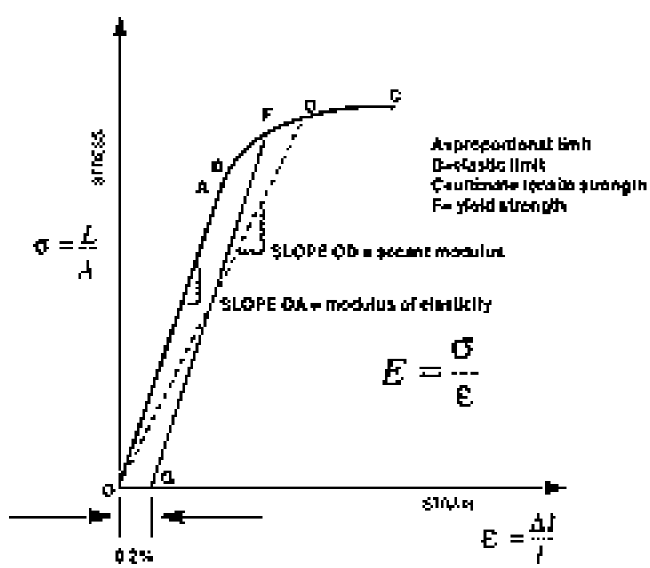


Figure 10 shows the plot of typical tensile test results. This is a Stress-Strain Curve, that characterizes the mechanical behavior of material in tension.

FIGURE 10: STRESS-STRAIN CURVE



Modulus of elasticity

Metal deformation is proportional to the imposed loads over a range of loads.

Since stress is proportional to load and strain is proportional to deformation, this implies that stress is proportional to strain. Hooke's Law is the statement of that proportionality.

$$\frac{Stress}{Strain} = \frac{\sigma}{\epsilon} = E$$

The constant, *E*, is the modulus of elasticity, Young's modulus or the tensile modulus and is the material's stiffness. Young's modulus is in terms of 10^6 psi or 10^3 kg/mm^2. The modulus is the slope of the initial linear portion of the stress-strain curve (line OA). If a material obeys Hooke's Law it is elastic. The modulus is insensitive to the material's temper. Normal force is directly dependent upon the elastic modulus.

Proportional limit

The greatest stress at which a material is capable of sustaining the applied load without deviating from the proportionality of stress to strain (point A). Expressed in psi (kg/mm^2).

Ultimate strength (tensile)

The maximum stress a material withstands when subjected to an applied load. Point C denotes the tensile strength in psi (kg/mm^2). Dividing the load at failure by the original cross sectional area determines the value.

Elastic limit

The point on the stress-strain curve beyond which the material permanently deforms after removing the load (point B).

Secant modulus

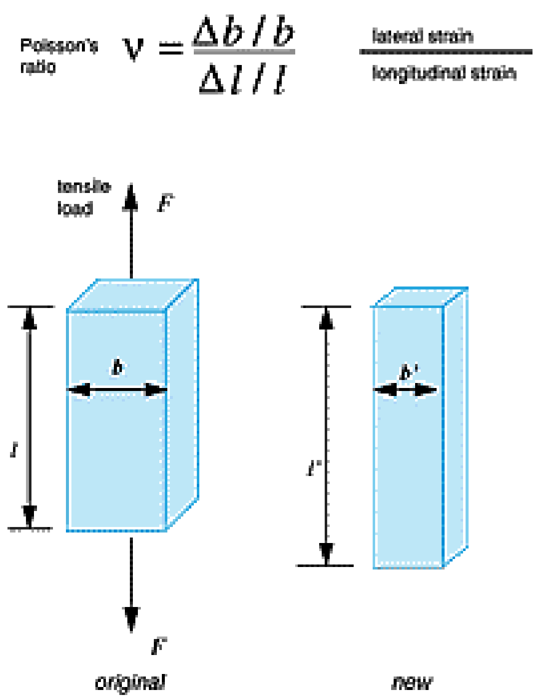
The ratio of stress to corresponding strain at any point on the stress-strain curve beyond the proportional limit is the secant modulus. The secant modulus at point D is the slope of line OD.

Yield strength

Constructing a parallel line to OA at a specified offset strain establishes the yield strength. The stress where the line intersects the stress-strain curve at point F is the yield strength at G offset. The parallel line is at 0.2% strain and the value is in units of psi (kg/mm^2).

Poisson's ratio

FIGURE 11: POISSON'S RATIO



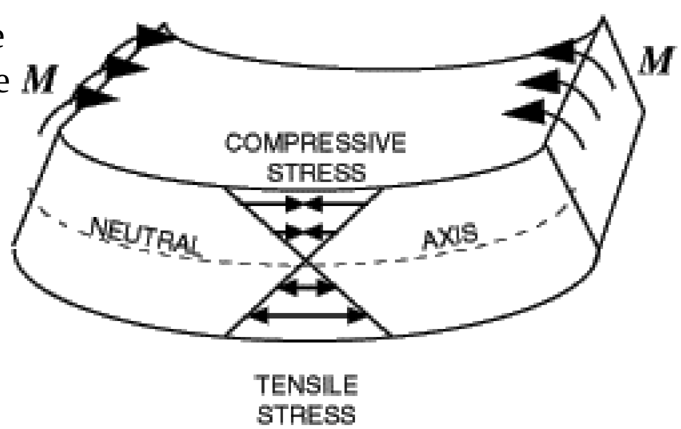
The ratio of the lateral to longitudinal strain is Poisson's ratio, ν. (Figure 11)

$$\nu = \frac{\textit{lateral strain}}{\textit{longitudinal strain}}$$

Poisson's ratio is a dimensionless constant used for stress and deflection analysis of structures such as beams, plates, shells and rotating discs. A typical value ranges between 0.30 - 0.35 for connector spring alloys. This ratio becomes important for a decreasing w/t ratio where plane stress conditions dominate. The ratio is slightly sensitive to processing since high levels of cold work provide preferred crystallographic texturing.

Bending stress

FIGURE 12: BEAM IN BENDING



When bending a piece of metal, one surface of the material stretches in tension while the opposite surface compresses (Figure 12). It follows that there is a line or region of zero stress between the two surfaces, called the neutral axis. Make the following assumptions in simple bending theory:

1. The beam is initially straight, unstressed and symmetric

2. The material of the beam is linearly elastic, homogeneous and isotropic.

3. The proportional limit is not exceeded.

4. Young's modulus for the material is the same in tension and compression

5. All deflections are small, so that planar cross-sections remain planar before and after bending.

Using classical beam formulas and section properties, the following relationship can be derived:

$$\textit{Bending stress, } \sigma_b = \frac{6\,PL}{w\,t^2}$$

$$\textit{Bending or flexural modulus, } E_b = \frac{4\,P\,l^3}{w\,t^3\,y}$$

Where: P = normal force
l = beam length
w = beam width
t = beam thickness
y = deflection at load point

The reported flexural modulus is usually the initial modulus from the stress-strain curve in tension. When available, take the value from a 4-point bend test.

The maximum stress occurs at the surface of the beam farthest from the neutral surface (axis) and is:

$$\textit{Max surface stress, } \sigma_{max} = \frac{M\,c}{\mathrm{I}} = \frac{M}{Z}$$

Where: M = bending moment

c = distance from neutral axis to outer surface where max stress occurs

I = moment of inertia (see Section V -- Design & Analysis)

Z = I/c = section modulus (see Section V -- Design & Analysis)

For a rectangular cantilever beam with a concentrated load at one end, the maximum surface stress is (Figure 13):

$$\sigma_{max} = \frac{3\,d\,E\,t}{2\,l^2}$$

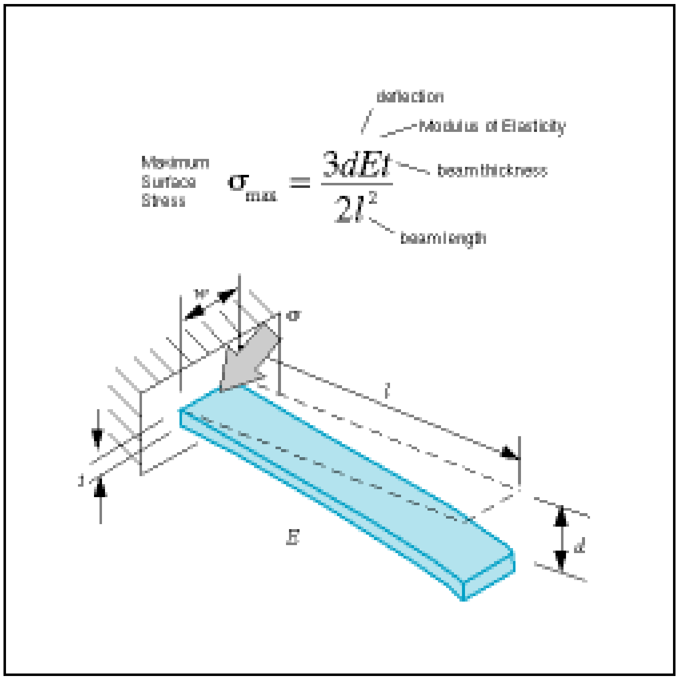
Where: d = deflection of the beam at the load

E = Modulus of Elasticity

t = beam thickness

l = beam length

FIGURE 13: MAXIMUM SURFACE STRESS



One of the methods to reduce maximum stress is to keep the strain energy in the beam constant while changing the beam profile. Additional beam profiles are trapezoidal, tapered and torsion.

Yielding

Yielding occurs when the design stress exceeds the material yield strength. Design stress is typically maximum surface stress (simple loading) or **Von Mises stress** (complex loading conditions). The Von Mises yield criterion states that yielding occurs when the Von Mises stress, σ_ν exceeds the yield strength in tension. Finite Element Analysis stress results use Von Mises stresses. Von Mises stress is:

$$\sigma_\nu = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}}$$

where σ_1, σ_2, σ_3 are principal stresses.

Safety factor is a function of design stress and yield strength. The following equation denotes safety factor, f_s.

$$f_s = \frac{Y\,S}{D\,S}$$

Where $Y\,S$ is the Yield Strength and $D\,S$ is the Design Stress.

Table 5 lists the critical material mechanical properties.

Hardness

Hardness is the resistance of a material to plastic deformation (usually by indentation). Hardness testing monitors process operations such as cold working, solution annealing, and age hardening. A hardness test does not measure a well-defined material mechanical property but provides a useful approximation. All tests in common use do not employ the same type measurements for basis. It is not surprising that there are no universal hardness-conversion relationships. Therefore, avoid converted values. **Diamond Pyramid (DPH)** and **Vickers** Hardness scales have the advantage that a continuous set of numbers covers the entire metallic hardness spectrum. This test allows direct hardness comparison of different gage products. (See Table 6)

More detailed information on hardness testing is available in the Brush Wellman TechBrief "Hardness Testing Beryllium Copper."

MATERIAL properties

Mechanical, cont.

Secondary (time related)

Stress relaxation

Stress relaxation is the gradual decay of stress at constant strain. Applying a fixed strain or displacement to a sample and measuring the load with time is the data collection technique. A series of data curves shows percentage stress remaining as a function of time and temperature (Larson-Miller technique). Temperature is more important than time for stress relaxation. Higher temperature means more rapid relaxation. The temperature in an actual connector depends on the surrounding temperature and heat generated in the connector. The connector material electrical and thermal conductivity decides the maximum temperature under different conditions. Alloys with higher conductivity will therefore reach a lower maximum temperature that is advantageous from a stress relaxation point of view.

Most connectors operate at temperatures less than one half the absolute melting temperature. Therefore, non-diffusion controlled mechanisms, including dislocation gliding, flow of grain boundaries, diffusion of vacancies and twinning govern the stress relaxation process. Figure 14 uses cantilever beam maximum surface stress to demonstrate stress relaxation conditions. The relationship between maximum surface stress and normal force dictates that stress relaxation decreases normal force (Figure 15).

FIGURE 14: STRESS RELAXATION CONDITIONS

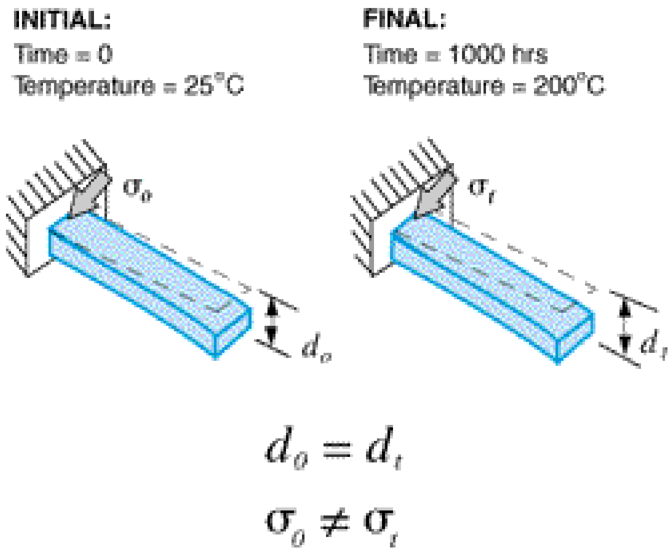
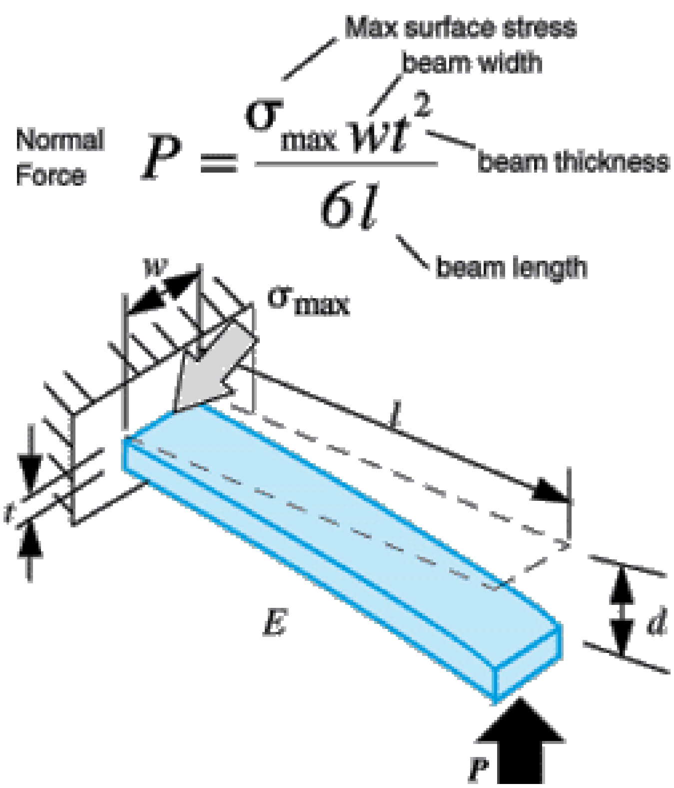


FIGURE 15: STRESS RELAXATION VS. NORMAL FORCE



Test procedure -- This procedure utilizes metallic test samples with cross sections of the approximate dimensions of the contact design. Figure 16 indicates the simple bend loads of the sample. Measurement of the permanent set of the beam occurs at various times after continuous exposure to elevated temperatures. Stressing alloys to a constant percentage of their individual yield strengths is preferable to a common numerical stress value for all alloys. The measured permanent set of the test beam reflects a loss of spring force, or a relaxation of the initial stress, as a result of the test conditions of time and temperature. The percentage loss at an established temperature and time is constant for any initial stress below the alloy's yield strength.

A Larson-Miller or stress relaxation plot presents stress relaxation data enabling performance prediction over a range of times and temperatures (Figure 17). The remaining stress indicates the contact alloy's ability to retain a portion of its stress. The stress relaxation plot predicts the percentage of remaining stress after exposure to a given elevated temperature over a specific time interval. Table 7 provides data on the relaxation characteristics of spring alloys at both 100°C and 200° C. Additional stress relaxation curves are available in the Brush Wellman document "Atlas of Stress Relaxation Curves for Beryllium Copper and Selected Copper Alloy Spring Materials."

FIGURE 16: STRESS RELAXATION TEST APPARATUS

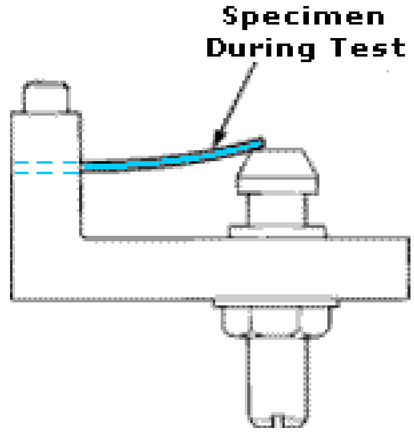
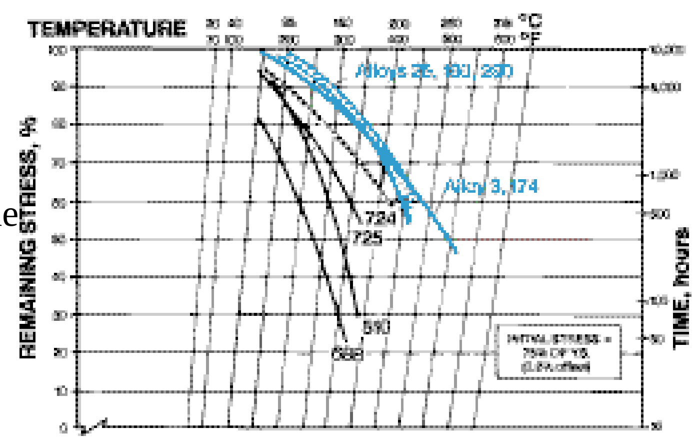


FIGURE 17: STRESS RELAXATION CURVES



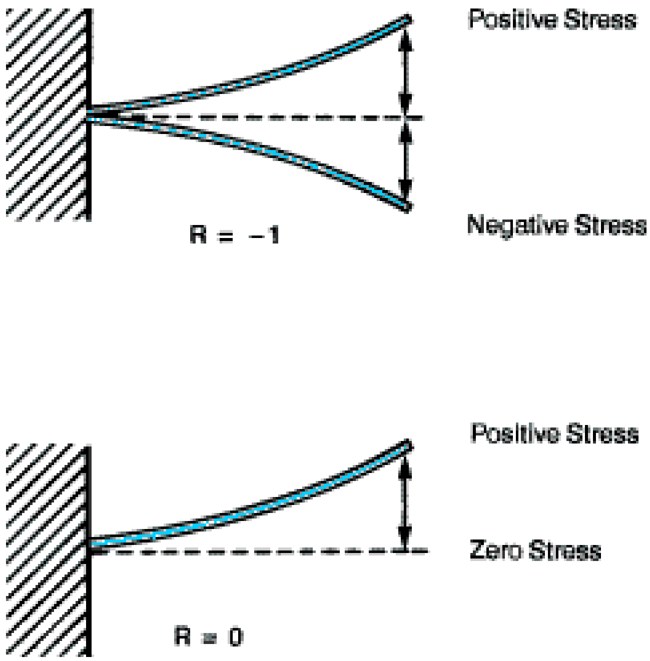
FEA modeling frequently requires the stress relaxation data as an empirical equation. This equation is in the form:

$$\% \text{ Remaining Stress} = A - B(\ln[t])^2$$

Where A and B are constants independent of initial stress and time yet dependent upon alloy, temper and temperature and t is time in hours. Table 8 is a summary of the parameters, A and B, for several high performance copper alloys.

Fatigue

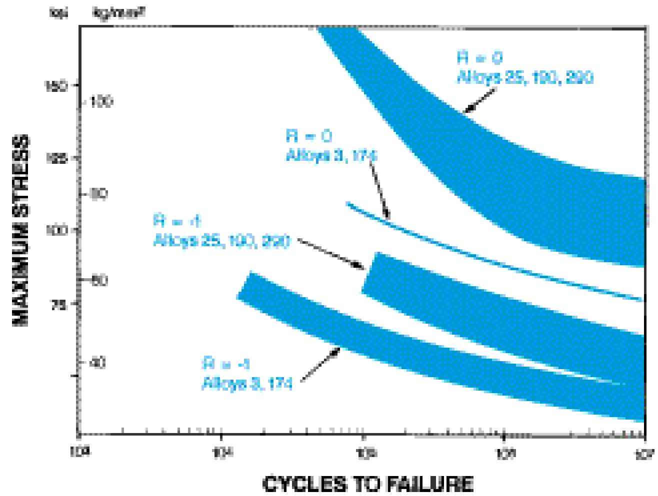
FIGURE 18: FATIGUE TEST CONDITIONS



Fatigue is the phenomenon leading to fracture under repeated or fluctuating stresses with a maximum value less than the tensile strength of the material. For typical connector applications, the number of cycles is typically 1K-10K in one way bending (R=0). The package governs the deflection. For switch and relay applications, reverse bending (R=21) is the fatigue mode. The fatigue life is the number of stress cycles prior to failure for a stated test condition. Figure 18 defines the fatigue testing conditions. The fatigue limit is the maximum stress that leads to fatigue failure in a specified number of cycles. Fatigue is a surface phenomenon affected by surface quality and edge condition. In order to improve the fatigue properties, it is advisable to remove surface damage of stamping and redistribute surface strains.

Conditions such as stress cycle, surface condition and environmental conditions strongly influence fatigue test results and fatigue performance.
Table 9 displays the fatigue strength of several connector spring alloys at 10^8 cycles. Figure 19 contains fatigue curves **(S-N curves)**.

FIGURE 19: FATIGUE CURVES



Technical Exchange

Section IV:
Material Properties
Primary

Section IV:
Material Properties
Mechanical - Tertiary

Design Guide -
Table of Contents

MATERIAL properties

Mechanical, cont.

Tertiary (Property Interdependence)

Normal force

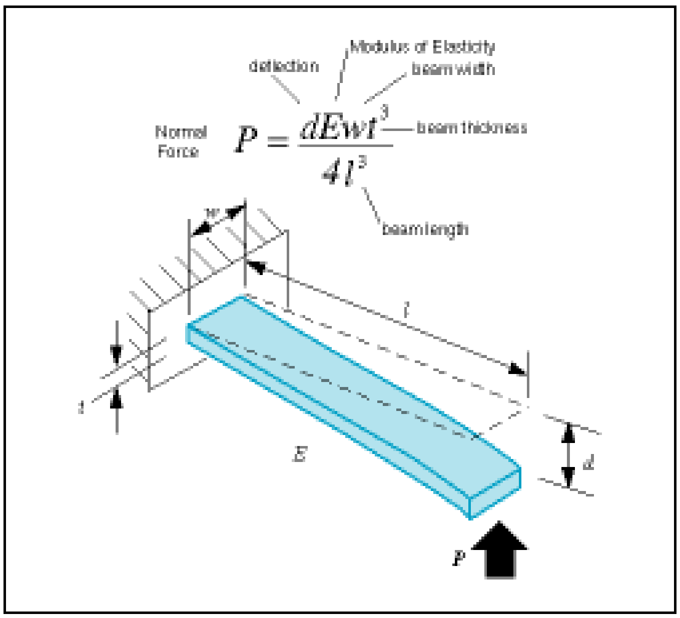
Normal or contact force is the most important attribute of a contact system directly related to contact reliability. Normal force is the force generated by surfaces contacting each other and perpendicular to those surfaces. For a cantilever beam type connector the following formula represents the normal force: (Figure 20)

$$\textit{Normal Force},\ P = \frac{d\,E\,w\,t^{3}}{4\,l^{3}}$$

Where: d = deflection of beam
E = Modulus of Elasticity
w = beam width
t = beam thickness
l = beam length

Normal force is also a function of

FIGURE 20: CANTILEVER BEAM NORMAL FORCE



maximum surface stress:

$$\text{Normal Force, } P = \frac{\sigma_{max} w\, t^2}{6\, l}$$

The frictional force depends on the normal force via the coefficient of friction. The frictional force is very sensitive to conditions at the interface. Insertion and extraction forces are frictional forces. Insertion force is dependent on the lead-in angle of the mating parts as well as the friction force. (Figures 21a & 21b)

$$\text{Friction Force, } F = \mu P$$

Where: F = friction force

μ = coefficient of friction

P = normal force

FIGURE 21a: FRICTION FORCES

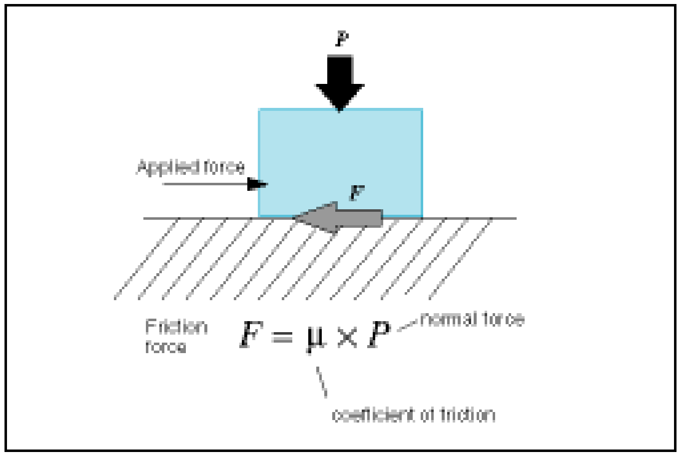
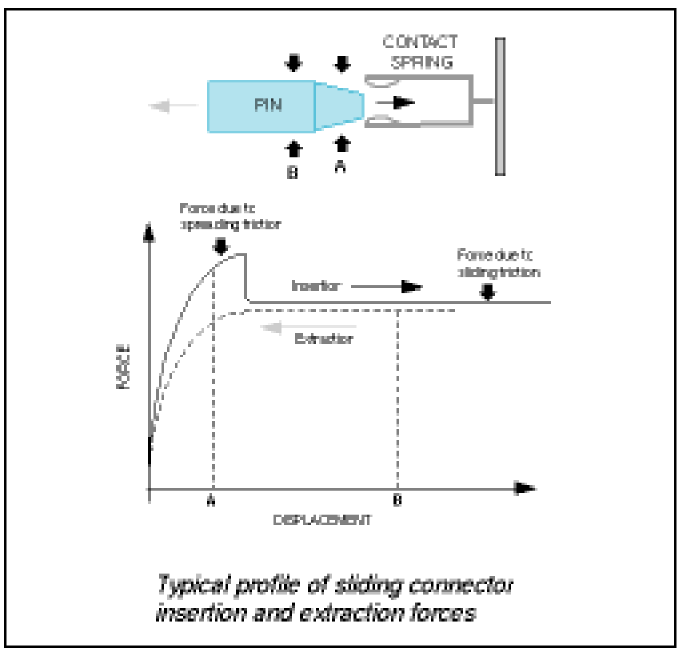


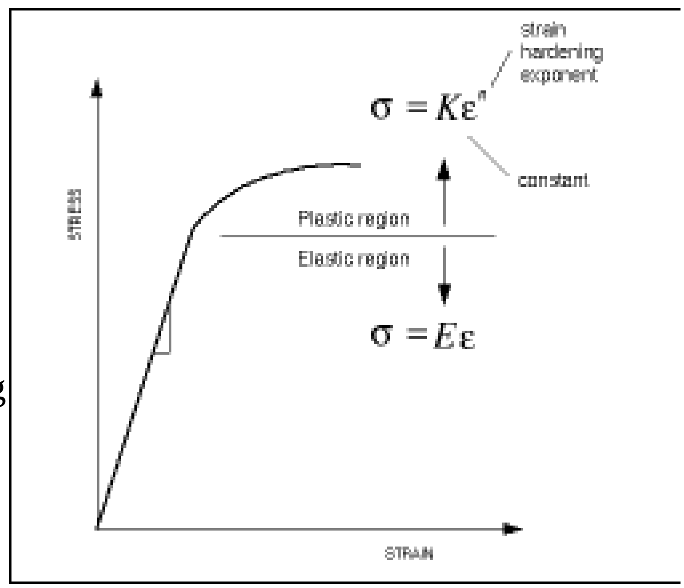
FIGURE 21b: INSERTION AND EXTRACTION FORCES



Interrelationships between the contact system and its normal force are in Table 10.

TABLE 10: NORMAL FORCE INTERRELATIONSHIPS	
Affected by Normal Force	**Affects Normal Force**
Friction Force (Insertion / Withdrawal)	Contact Spring Rate
Wear Characteristics	Contact Pre-Load
Contact Spring Stresses	Contact Beam Deflection
Contact Housing Stresses	Permanent Set
Contact Resistance	Stress Relaxation

FIGURE 22: STRAIN HARDENING



At small deflections, for a given contact configuration and a constant deflection (strain), the normal force (stress) of the contact is a function only of the modulus of elasticity.

At large deflections, above the yield strength, the rate of increase in normal force with deflection decreases. This leveling off in force occurs as a result of plastic deformation, or permanent set, along the flexed portion of the beam. After large deflections, the contact will not return to its initial unstressed position.

In the plastic strain region, above the yield strength, the stress-strain behavior is no longer linear (Figure 22). In this region, where the alloy is subject to strain hardening, the following equation can be used to predict the true stress, σ, for known levels of strain.

$$\sigma = K \varepsilon^{n}$$

Where ε is the true plastic strain, *K* is a constant and *n* is the strain hardening exponent. Composition, the amount of cold reduction and the alloy's processing history influence the value of *n*. The following table provides representative values of the strain hardening exponent for beryllium copper alloys. (See Table 11)

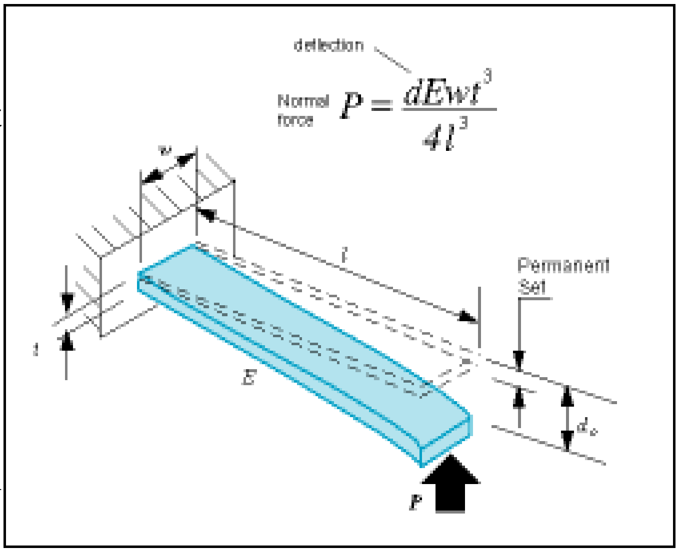
TABLE 11 - STRAIN HARDENING EXPONENT

Brush Alloy	n	K (ksi)	K (kg/mm^2)
25 A	0.49	176	124
25 1/4 H	0.17	137	96
25 H	0.07	170	120
190 HM	0.06	198	139
3 AT	0.13	167	117
174 HT	0.07	153	108

Permanent set

Permanent set is the plastic deformation that remains after releasing the deformation producing stress (Figure 23). This is a result of repeated deflections during component mating, oblique insertions or insertions of oversized test probes. The contact performance degradation from permanent set reduces the normal force exerted on the pin by reducing the amount of available deflection. The material property of importance is yield strength. Toughness and resilience are functions of yield strength.

FIGURE 23: PERMANENT SET



Toughness of a material is its ability to absorb energy in the plastic range. The ability to withstand occasional stress above the yield stress without fracturing is desirable. Toughness is the area under a stress-strain curve up to the maximum stress (Figures 24a & 24b). The following equation approximates toughness:

Toughness = (YS x US) + 1/2 (TS - YS) US

Where: *YS* = 0.2% offset yield strength

TS = ultimate tensile strength

US = uniform strain

FIGURE 24a: TOUGHNESS DEFINITION

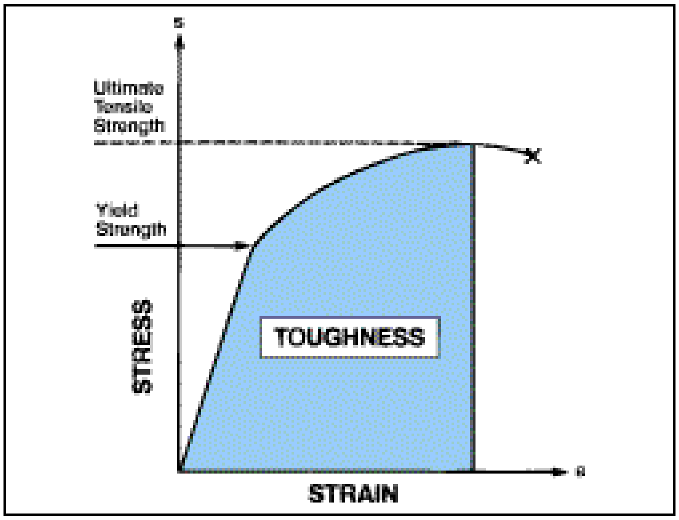
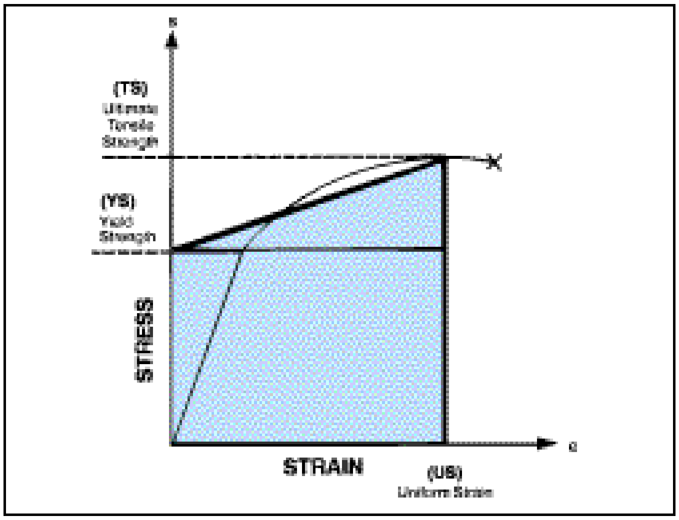


FIGURE 24b: TOUGHNESS APPROXIMATION

This area is an indication of the work per unit volume done on the material without causing it to rupture. Toughness is a parameter that comprises both strength and ductility.



Resilience is the ability of a material to absorb energy when deformed elastically and to return it when unloaded. The measurement of **modulus of resilience**, *U*, is the strain energy per unit volume required to stress the material from zero stress to the yield stress. The following equation defines the resilience:

$$U_R = \frac{(YS)^2}{2E}$$

Where: YS = 0.2% offset yield strength

E = Modulus of elasticity

This equation indicates that the ideal material for resisting energy loads in applications where the material must not undergo permanent distortion is one having a high yield stress and a low modulus of elasticity. Resilience and toughness are approximations of durability.

Bauschinger effect results in a loss of stress upon applied stress reversal.Loading against the forming direction will result in a reduction of normal force and produce permanent set at loads less than allowed by the contact design. Deflection in the forming direction will show normal force and permanent set as predicted in design. Plastic deformation increases yield strength in the direction of plastic flow and decreases in the other direction. This effect is a function of yield strength in that a greater yield strength results in lower reverse loading stress loss. Stress relief can minimize the effect after forming.

Environmental Considerations

During their normal operation, contacts are subject to mechanical stresses. Contacts experience additional environmental stresses including elevated temperatures and stress levels as well as harsh environmental exposure. Elevated temperature conditions may result from ambient or resistive heating. Tensile properties are temperature dependent (approximately 10% for each 100°F or 56°C). A number of factors contribute to a stress level above the design point. These are dependent upon the material and geometry, thermal level, residual stress and functional stress in a contact. Corrosion resistance is critical for exposure to harsh environments.

MATERIAL properties

Electrical and Thermal Properties

Coefficient of Thermal Expansion (CTE)

The fractional change in length of a material per degree of temperature change as compared to its length at a reference temperature, usually 0°C. Differences in CTE result in a thermal mismatch between two components. The thermal expansion coefficient of beryllium copper is independent of alloy content over the temperature use range. Table 12 gives the thermal expansion coefficients.

FIGURE 12 - THERMAL EXPANSION COEFFICIENT

Alloy	Thermal Expansion Coefficient (in/in/°F, 70°F to 400°F) (21°C to 204°C)
25 M25 165	9.7×10^{-6}
3 174	9.8×10^{-6}
260	11.1×10^{-6}
194	9.8×10^{-6}
510	9.9×10^{-6}
521 688	10.1×10^{-6}
654	9.7×10^{-6}
725	9.2×10^{-6}

Electrical Conductivity

Electrical conductivity, γ, is the reciprocal of the material's bulk resistivity. The material electrical resistivity, ρ, is the electrical resistance of a material per unit length and cross sectional area.

$$\rho = \frac{R\,A}{l}$$

Where: R = resistance (ohm)

A = cross sectional area (in^2 or cm^2)

l = length (in or cm)

Copper alloy electrical conductivity is in units of %IACS. **%IACS** is the acronym for Percentage of International Annealed Copper Standard. The pure copper standard of 6.79×10^{-7} ohm-in (1.72×10^{-6} ohm-cm) at 20°C equals a value of 100%.

Thermal Conductivity

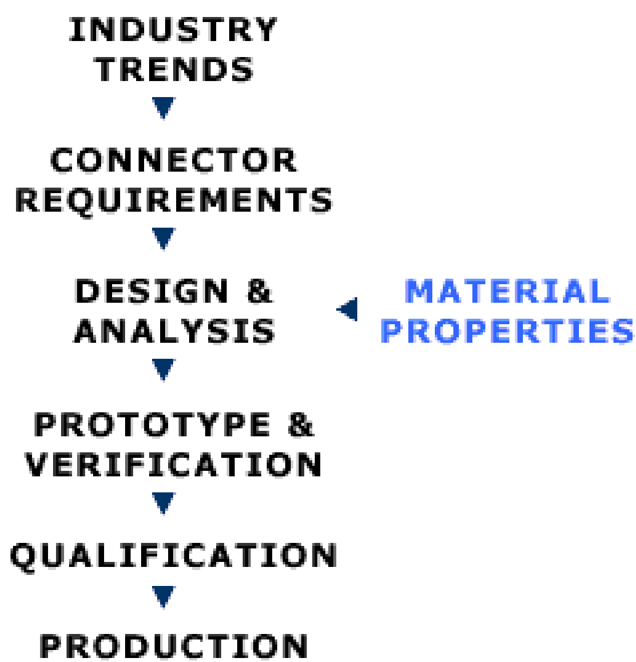
Thermal conductivity, κ, is the ease with which a material dissipates heat. Formally, thermal conductivity is the rate of heat flow per unit time in a homogeneous material under steady state conditions, per unit area, per unit temperature gradient in a direction perpendicular to that area. The following equation approximates κ for temperatures above room temperature:

$$\kappa = \frac{7.1 \times 10^{-6}}{\rho} + 0.1$$

Where: κ = thermal conductivity (W/cm°C)

ρ = resistivity at 20°C (ohm-cm)

Table 13 shows the thermal and electrical conductivity as well as conductivity product of several contact materials.



Temperature rise

Temperature rise is a function of the bulk resistance of the material. The material resistivity and contact geometry define the bulk resistance. The contact temperature rise depends on thermal dissipation of heat generated which in turn depends on the thermal conductivity of the spring material, the magnitude of the electrical current flow and the heat sinking or convection of the connector.

The maximum, steady state temperature rise of a contact beam, accounting for the effects of resistive heating and heat transfer can be predicted by the following equation:

$$\Delta T = \frac{J^2 L^2}{2 \gamma \kappa A^2}$$

Where: ΔT = temperature rise (°F)

J = current (amps)

L = beam length (in)

A = cross-sectional area (in^2)

γ = electrical conductivity (A/V in)

κ = thermal conductivity (V A/in F)

The conductivities are the only two material properties influencing temperature rise in a connector. This equation provides a conservative estimate of temperature rise in that it makes no allowance for heat loss through convection or radiation.

It is apparent that temperature rise is inversely related to the product of a material's electrical and thermal conductivities. It is important that a connector material not only minimize resistive or Joule heating through electrical conductivity, but also dissipate the heat which is generated in the contact through the alloy's thermal conductivity.

Power Properties

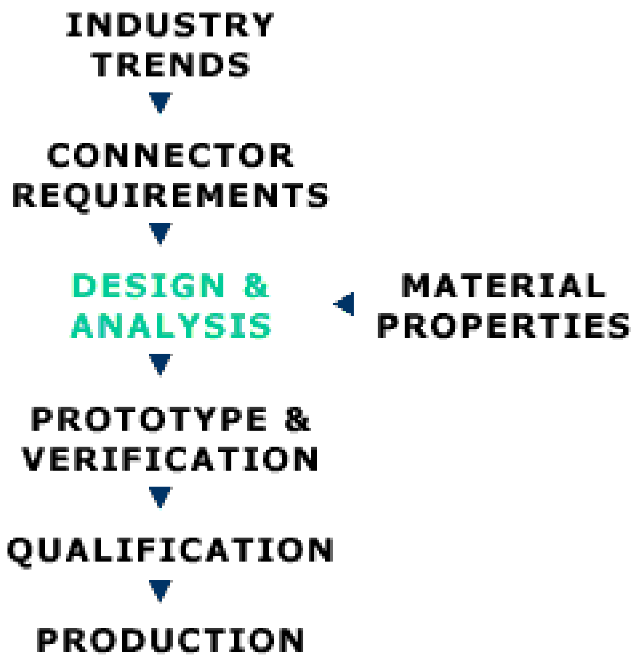
Both magnitude and stability of contact resistance are critical for power distribution requirements. Joule or resistive heating, which is proportional to connector resistance, results in increases in connector operating temperature. A specified temperature rise (typically 30°C) determines the current capacity or rating. Power may be carried in single dedicated contacts or through multiple parallel contacts.

Signal Properties

Signal distribution requirements center around maintaining the integrity of the signal waveform. Bulk resistance, impedance, propagation delay, crosstalk and low level circuit resistance are critical properties. Conventional copper strip material connectors are effective up to a 1 GHz operating frequency when proper considerations are given to electrical design.

DESIGN & analysis

In general, connectors and interconnection systems transport data and power signals in electrical and electronic systems. Poorly designed connections can ruin otherwise well designed systems. The integrity of the entire system depends on the conductors, terminals, connectors, sockets, etc.



Methods

Computer Aided Design (CAD)

Connector designs today are frequently constructed as mathematical solid models instead of two-dimensional (2D) drawings due to the availability of computer aided design software packages. A solid model is one that represents a shape as a three-dimensional (3D) object having mass properties.

The main reasons for the move to solid models is that solid modeling packages can serve as a means of portraying parts for study by cross-functional concurrent engineering teams. Providing data for analysis tools and numerically controlled machines are two such uses.

Design for manufacturability

The need for higher volume production, enhanced interchangeability, and cost reduction has led to the development of what has become known as statistical tolerance analysis. The primary aim of such analysis is the computation and subsequent analysis of the mathematical probabilities related to the likelihood of exceeding manufacturing specifications. The underlying concepts of statistical analysis are being integrated with the notion of designing for manufacturability. The basic thrust of this philosophy relates to the simultaneous optimization of customer satisfaction and production costs. This implies a marriage between engineering tolerances and manufacturing capability. By jointly studying assembly tolerances and manufacturing performance from a statistical point of view, an organization can enjoy higher manufacturing yields and lower cost.

Section V: Design & Analysis Table of Contents Detail

The first sections discuss the various analysis methods; the last section discusses Brush Wellman's design review services.

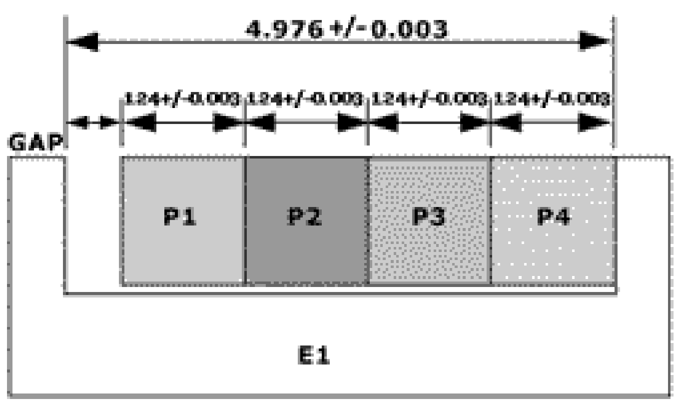
DESIGN & analysis

Tolerance Analysis

Tolerance analyses are tools to achieve the goal of higher product quality by minimizing tolerance build-up during assembly and mating. Several types of analyses are available:

Arithmetic Worse Case (AWC) is the simple linear addition and subtraction of tolerances, each at their worse case condition. This method produces an overly conservative design and does not take into account the statistical probability of an interference fit. The analysis considers the linear extremes of design specifications without regard to process capability. Worse case analysis applies best when the number of parts in an assembly is less than four. (Figure 25)

FIGURE 25: TOLERANCE ANALYSIS



GAP = E1 - (P1+P2+P3+P4)
MIN GAP = 0.016 +/- 0.015 = 0.001

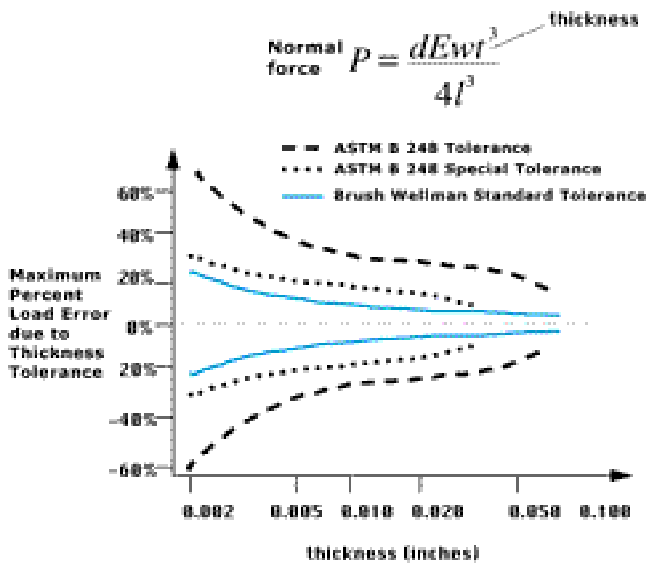
Root Sum of Squares (RSS) is less conservative than AWC tolerance analysis. RSS assumes that the print tolerance equals +/- 3 standard deviation (σ) limits and part nominal equals print nominal. This analysis exploits the manufacturing probability that a part is not always at its minimum or maximum value. It does not take into account process mean shifts (tool wear) and assumes the process is always centered.

Dynamic Root Sum of Squares (DRSS) is less conservative than RSS analysis. This method factors in the process mean shift by adding the actual process capability index (C_{pk}) into the equation. Whenever process capability at the component level decreases, the likelihood of assembly decreases. This method inflates the assembly standard deviation, but has little impact on the overall assembly mean (random process mean shift).

Static Root Sum of Squares (SRSS) postulates sustained mean shift conditions of each component in the assembly.

In addition to assembly tolerances, tight thickness tolerance is essential to the manufacture of precision stamped strip metal springs since contact or normal force varies as a cubic function of thickness. The normal force equation illustrates this. Figure 26 demonstrates the potential normal force error for different tolerance levels. **Tables 14** & **15** provide strip and wire dimensional tolerances. Tighter tolerances than listed can also be achieved. Contact Brush Wellman with your specific requests.

FIGURE 26: CONTACT LOAD ERROR DUE TO THICKNESS TOLERANCE



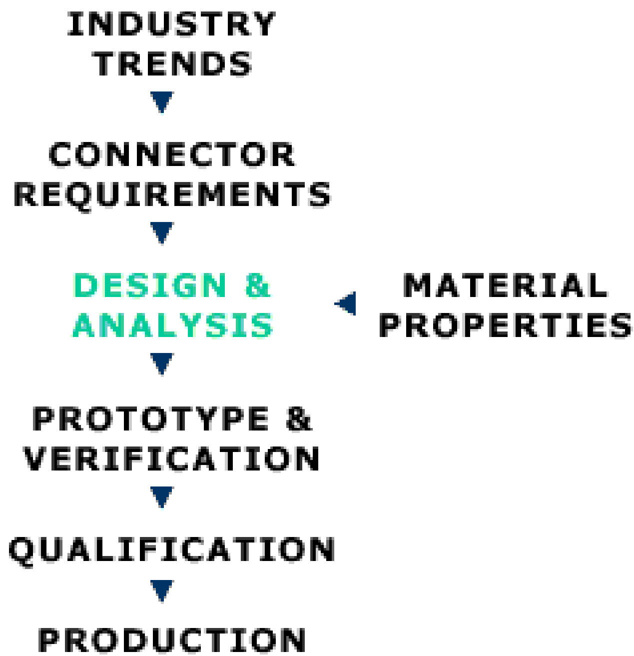
Dimensional tolerances

Strip
(rolled and mill hardened strip only)

(See Tables 14a & b)

DESIGN & analysis

Structural analysis



In the design and analysis of any connector, a systematic approach is desirable. Engineers new to connector design often neglect the effects of stresses caused by assembly, handling, shipping, processing, temperature and other environmental changes. The simple analysis techniques presented here assist the design engineer in developing new designs by showing how to handle anticipated loading while keeping stress and strain within acceptable limits. This section applies simplified classical stress and deflection equations to connector designs. Increased complexity designs requiring very accurate results require more exact classical methods or computerized finite element analyses.

Loads

The first step in analyzing any part is to determine the part loading. These loads generally fall into two categories:

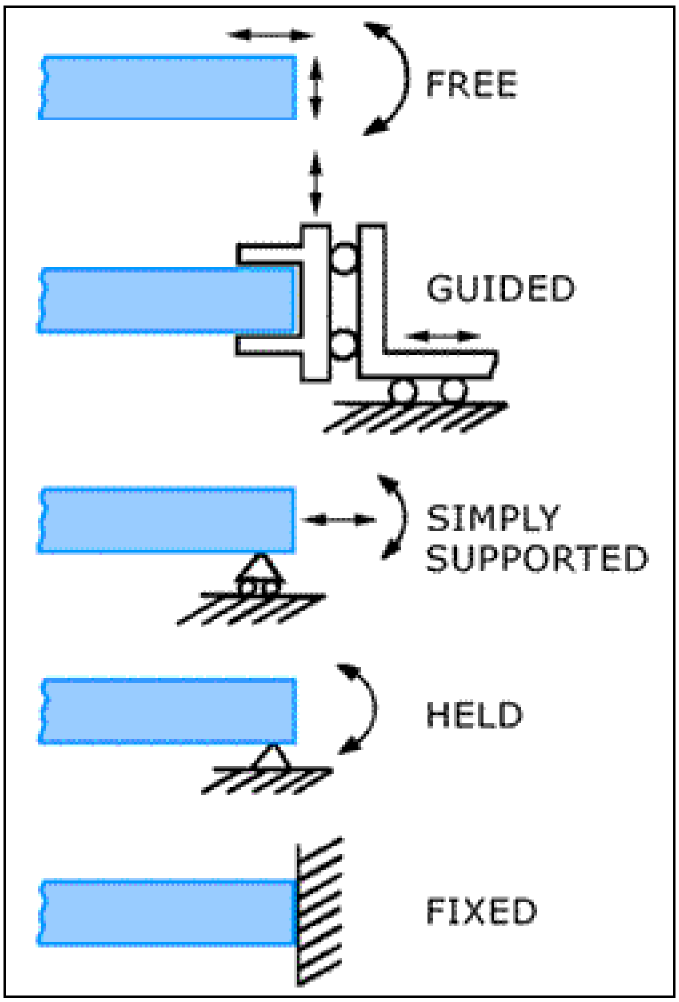
Directly Applied Loads -- Loads applied to defined areas of the part, either concentrated at a point, line or boundary or distributed over an area. Service conditions determine the magnitude and direction of such loads.

Strain Induced Loads -- Frequently, loading is a result of deflection. The actual load results from the structural reaction of the part to the applied strain. Unlike directly applied loads, strain induced loads depend on the modulus of elasticity of the material.

Support Conditions

For the part to remain in equilibrium there must be equal forces acting in the opposite direction to the applied forces during loading. The balancing forces are the reactions at the supports. Several support conditions are in Figure 27:

FIGURE 27: SUPPORT CONDITIONS



Free (Unsupported) -- edge of body is totally free to translate or rotate in any direction

Guided -- similar to free end except that the edge is prevented from rotating

Simply supported -- transverse displacement in one direction is restricted

Held (Pinned) -- similar to simply supported except that only rotations are allowed.

Fixed (Clamped) -- prevents transverse displacements and rotations at an end support firmly embedded in a fixed wall.

When analyzing a particular design using classical mathematical equations, the accuracy of the result depends on the assumptions used during the calculations.

Simplifications and Assumptions:

1. The part under load can be broken down into one or more simple structures, beams, plates for analysis.

2. The material being analyzed may be considered to be linearly elastic, homogeneous and isotropic.

3. The equations assume that the load is a single concentrated or distributed static load, gradually applied for a short period of time and then removed. However, the same equations can analyze relaxation and fatigue loads, using the appropriate modulus.

4. The part being analyzed has no residual stress.

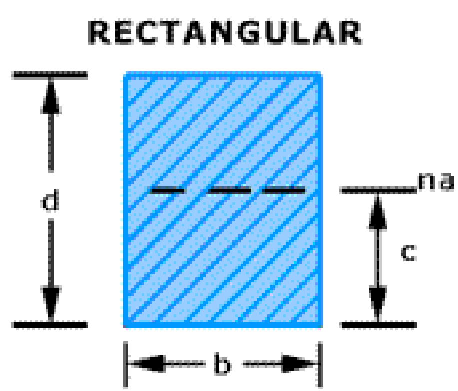
5. The equations apply to regions that are remote both from the point of application of the load and from any stress riser (shoulder, hole or change in dimension of the part).

6. The equations may be used at shoulders, holes, or other sudden dimensional changes as long as appropriate stress concentration factors are used.

Section properties for some common cross-sections (Figure 28):

FIGURE 28: COMMON CROSS-SECTION PROPERTIES

Rectangular

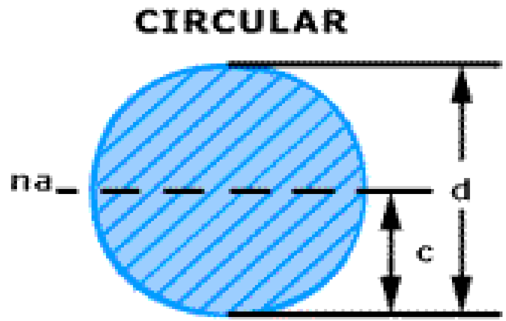


Area, A = bd

$$\text{Moment of Inertia, I} = \frac{bd^3}{12}$$

$$\text{Section Modulus, } Z = \frac{bd^2}{6}$$

Circular



$$Area,\ A= \frac{\pi\, d^{2}}{4}$$

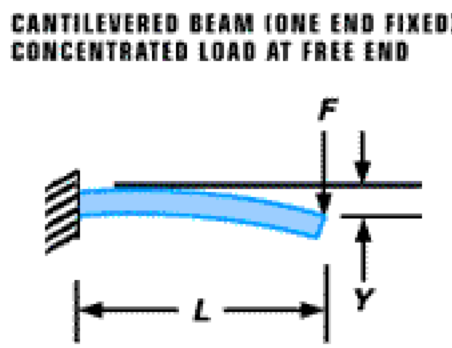
$$Moment\ of\ Inertia,\ \mathrm{I}= \frac{\pi\, d^{4}}{64}$$

$$Section\ Modulus,\ Z= \frac{\pi\, d^{3}}{32}$$

Maximum stress and deflection equations for selected beams (Figure 29):

FIGURE 29: MAXIMUM STRESS AND DEFLECTION EQUATIONS

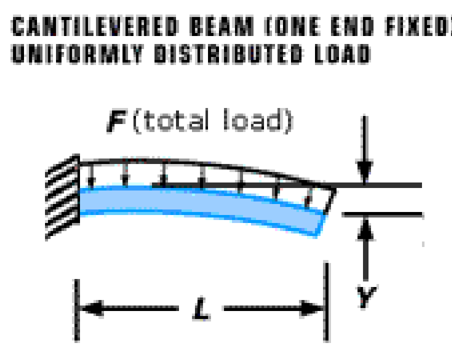
Cantilevered beam (one end fixed), concentrated load at free end



$$\text{(At support)}\ \ Stress,\ \sigma= \frac{F\, l}{\ }$$

$$\text{(At load)}\ \ Deflection,\ y= \frac{F\, l^{3}}{3\, E\, \mathrm{I}}$$

Cantilevered beam (one end fixed), uniformly distributed load



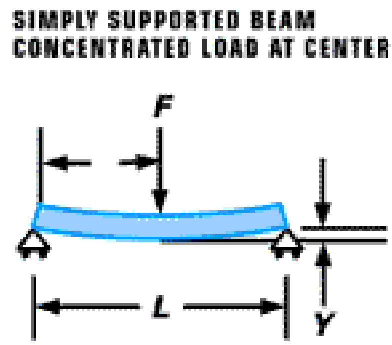
$$\text{(At support)}\ \ Stress,\ \sigma= \frac{F\, l}{2\, Z}$$

$$\text{(At free end)}\ \ Deflection,\ y= \frac{F\, l^{3}}{8\, E\, \mathrm{I}}$$

Simply supported beam,
concentrated load at center

(At load) *Stress*, $\sigma = \dfrac{F\,l}{4\,Z}$

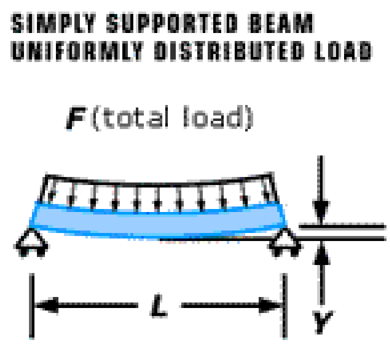
(At load) *Deflection*, $y = \dfrac{F\,l^3}{48\,E\,I}$



Simply supported beam,
uniformly distributed load

(At center) *Stress*, $\sigma = \dfrac{F\,l}{8\,Z}$

(At center) *Deflection*, $y = \dfrac{5\,F\,l^3}{384\,E\,I}$



As shown, handbook solutions are available for simple structures and loading conditions. Additional cantilever beam equation transforms are located in the Appendix.

Complicated shapes or complex loading conditions require a more accurate method than standard beam equations. Finite Element Analysis is one such method.

Technical Exchange

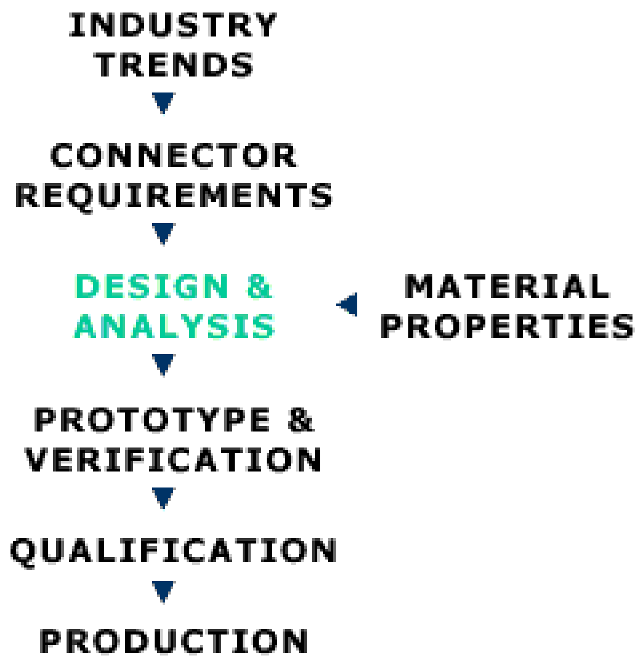
Section V: Design & Analysis Tolerance Analysis

Section V: Design & Analysis Finite Element Analysis

Design Guide - Table of Contents

DESIGN & analysis

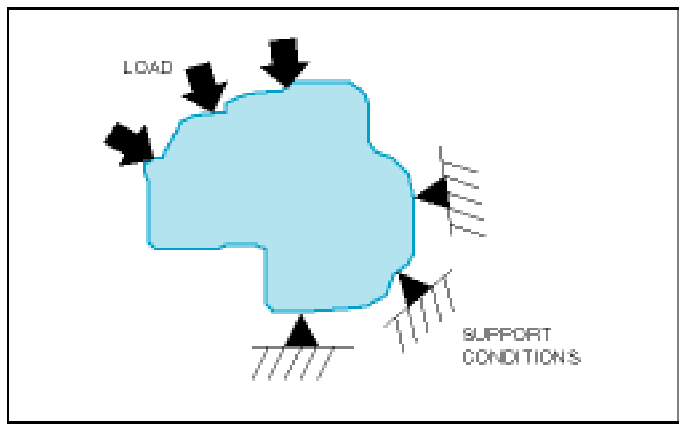
Finite Element Analysis



Finite Element Analysis (FEA) is a computer based technique for finding stresses and deflections in a structure using selected load cases. The method divides a structure into small elements with easily defined stress and deflection characteristics based on a series of differential equations. The finite element method solves these equations with global matrices using a computer program. FEA solves mechanical and thermal problems and models complicated features undergoing static and dynamic loading using the following steps:

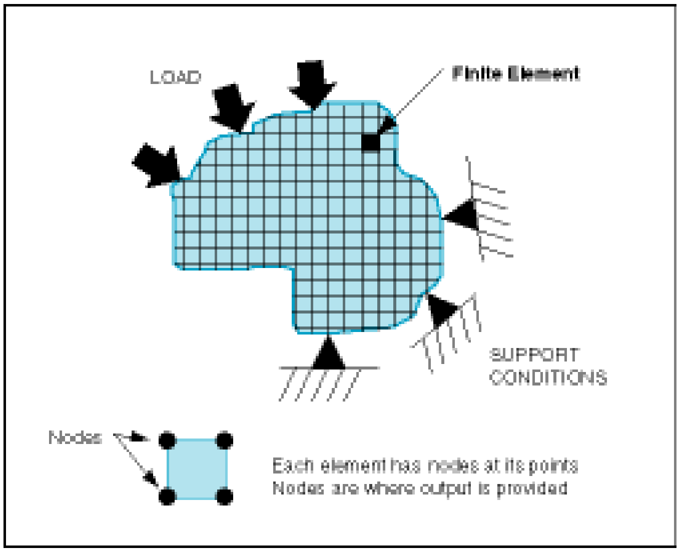
1) **Geometry Development** -- The first step in Finite Element Analysis is the creation of a model that breaks a structure into simple standardized shapes or elements with a common coordinate grid system. The coordinate points, called nodes, are locations in the model that provide output data (Figure 30a & b). Strains, displacements and stresses are transmitted among elements through common nodes. CAD creates the three-dimensional (3D) representation of the product geometry as previously described. Element selection is a function of product geometry and loading conditions. The element selected affects the results as each element has characteristic properties. A model can use more than one type of element.

FIGURE 30a: FINITE ELEMENT MODEL



The list below contains some of the element types and their properties:

FIGURE 30b: FINITE ELEMENT MODEL



- 2D elements = all forces and displacements act in plane
- Axisymmetric elements (2D) = node displacements in radial and axial directions
- 3D elements = forces and displacements in all three dimensions or complex geometry
- specialty elements = shell, plate and beam

2) **Material Property Assignment --** Modulus of elasticity or rigidity and Poisson's ratio define material properties for each element. A stress-strain curve represents the material properties for a non-linear material condition (elastic-plastic). Section VI -- Test Methods and Data defines one such curve.

3) **Mesh Generation** -- Based on the element types selected, automatic mesh generation subdivides the geometry into a finite number of elements. The element density within each segment of the product geometry is either chosen or automatically determined. The nodes and elements defining the geometry of the structure comprise a mesh. The finite element program calculates nodal stiffness properties for each element and arranges them into matrices. The appropriate matrix transformation generates a global stiffness matrix from the existing element matrix.

4) **Boundary Conditions** -- The appropriate boundary conditions apply constraints to the model (fixed, simply supported, etc.).

5) **Load Application** -- Applies loads to the model (force, pressure, temperature, etc.)

6) **Run Analysis** -- The program processes the equation matrices with applied loads and boundary conditions to calculate displacements, strain, natural frequencies or other data specified by the program. This provides a stress distribution across the entire model. The high stress regions should also have the highest element density. Each individual element should have a small stress gradient across itself. A finer mesh increases the accuracy of the model. However, the computer run time is longer. Various adaptive methods find the critical regions in the model and make the necessary mesh refinement to reduce the error for the next iteration before reaching convergence.

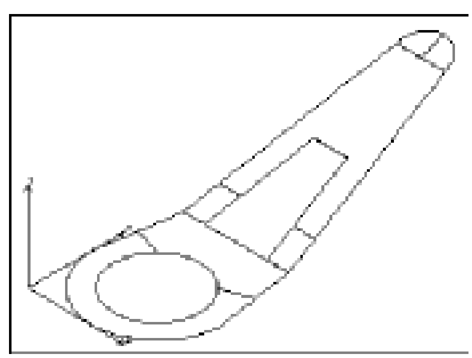
Static analyses such as deflection, stress and strain under a constant set of applied loads are the most common analyses. The material assumption is linear elastic, but analyzing non-linear behavior such as plastic deformation, creep and large deflections is possible.

FEA can predict relative changes in deflection and stress better than absolute deflection and stress. The proportional difference of two structures is more accurate than the absolute results.

7) **Results** -- Results usually include graphical display of the solution, an output file, and hard copy of the results images. (Figure 31)

FIGURE 31: FINITE ELEMENT MODEL EXAMPLE

WIREFRAME GEOMETRY



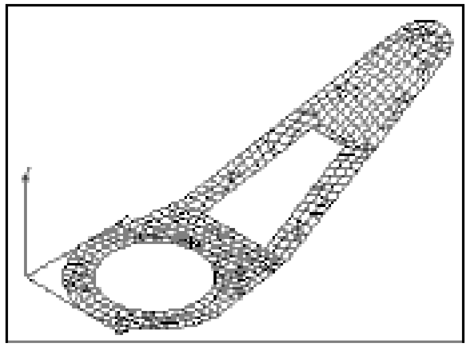
Typical connector FEA results include:

- Deflected contact shapes during and after mating
- Beam and contact stresses
- Interferences
- Normal forces
- Mating force vs. deflection curve
- Thermal effects
- Behavior under shock and vibration

8) **Data Correlation** -- Experimental data is collected to correlate the FEA model results and to formulate a baseline.

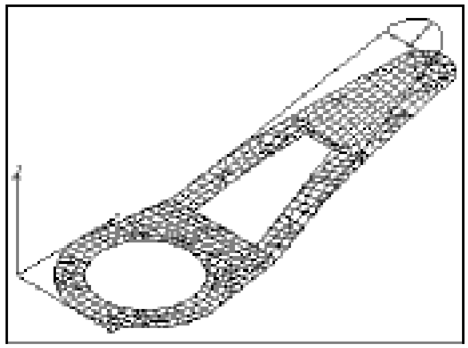
9) **Design Optimization** -- After comparing the baseline results, design modification and remodeling are available. This iterative process is design optimization. Design optimization combines the engineering requirements, geometric parameters, CAD model and performance goals into a computer simulation to achieve the optimum design.

FEA MESH



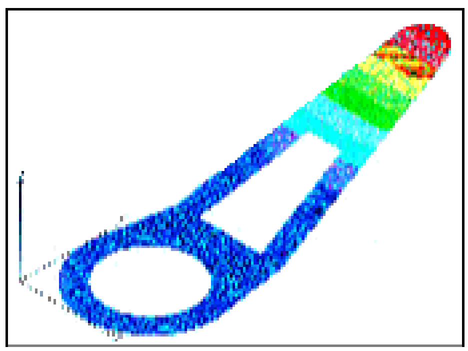
Caveats for FEA analysis:

DEFORMED SHAPE



Traditional Finite Element Analysis programs analyze linear problems, assuming linear elastic material behavior, small displacements relative to the overall dimensions, and constant boundary conditions. Another requirement when assuming linearity is reversibility of the process modeled. While this condition satisfies most cases in load deformation analysis, the whole premise of contact stamping is to impart permanent and irreversible deformation to the workpiece. The nonlinearities encountered in contact stamping fall into three major categories:

DISPLACEMENT PLOT



- **Material:** Elastoplastic material, strain rate sensitivity, and anisotropic behavior due to rolling.
- **Boundary Conditions:** Nonlinearity due to constantly changing contact between tools and workpieces.
- **Geometry:** The workpiece undergoes large rotations and deformations.

Forming history -- In order to account for the residual stresses due to the forming history of a connector spring contact, redefine the FEA boundary conditions after forming as follows:

1. Input boundary conditions for forming

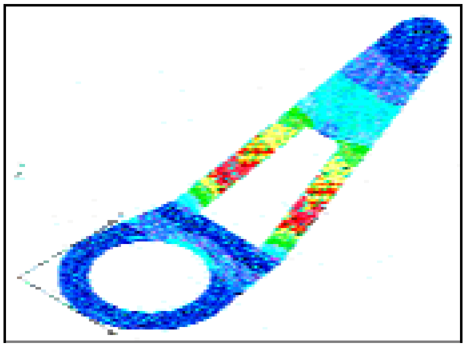
2. Use stress-strain curve as material input and then "form" the "part"

3. Elastically remove the forming "tooling" and allow stresses to redistribute

4. Redefine the boundary conditions for the "part" model

5. Deflect the FEA "part" and asses the performance.

VON MISES STRESS PLOT



One MUST use nonlinear code that can suitably remesh when forming displacements are large enough to create an error due to shifting of the node coordinate system. The explicit method takes a large number of steps to represent the severe nonlinearities by many small linearized increments. In addition, use an elastic-plastic material model that includes work hardening for the forming step.

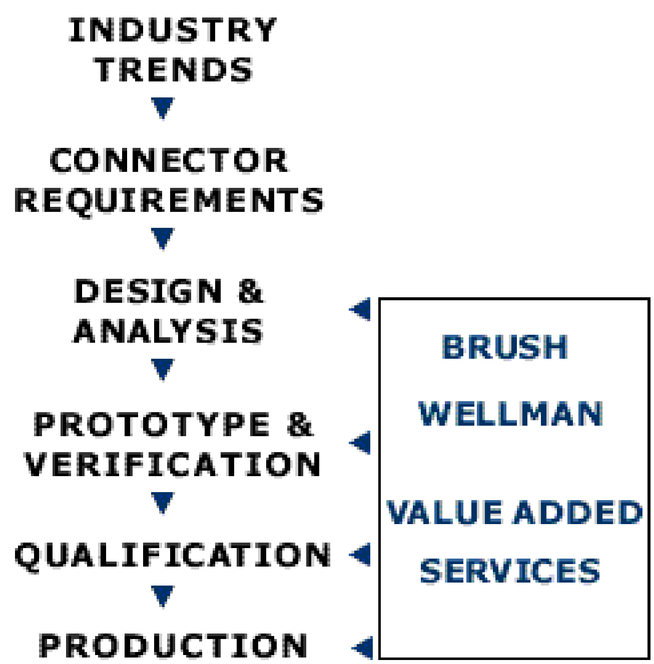
Electrical analysis

Increasing integrated circuit speeds to greater than 50 MHz requires electrical analysis or modeling. At those speeds, analog effects increase in interconnects, requiring verification with analysis tools.

Similar to mechanical Finite Element Modeling, electrical modeling uses a Boundary element method (BEM) field solver to determine resistance and per meter capacitance and inductance of the contact geometry. The time domain solver (SPICE - Simulation Program with Integrated Circuit Emphasis) uses the BEM results to determine the interconnecting media's effect on signal integrity. These include propagation delay, ringing and reflections and crosstalk effects. This analysis requires the electrical length of the conductor and the wavelength of the fastest signal. Inputs also require conductor width, thickness, dielectric height and constant.

DESIGN & analysis

Design Review



Prior to the prototyping stage, design reviews ensure that the original requirements of the connector are achievable. An available resource is Brush Wellman's services including design assistance, technical service and a worldwide distribution network.

Brush Wellman Services

Alloy selection -- With more than 200 strip metals listed by the Copper Development Association (CDA), paring those down to a handful with the proper attributes is useful to connector design engineers.

Design assistance -- Brush Wellman has the resources to perform simple stress calculations as sanity checks as well as in-house capability to perform more complex Finite Element Modeling.

Toll free customer service -- 1-800-375-4205 -- technical service staff
(or, if you prefer, email us)

Technical staff -- Research and development organization

Technical specialists -- Application specific specialist to assist with design and fabrication

Literature -- Current literature is available for each product

Library -- Technical library with electronic database systems

Educational seminars -- BeCu Update seminars as well as in-house specific seminars.

Custom fabrication -- Capabilities and engineering facility in Elmore plant

Failure analysis -- Both the Cleveland and Reading laboratories are available to perform routine failure analysis on the material.

Worldwide network -- Brush Wellman maintains a worldwide network to guarantee on time delivery of base metal that consist of the following:

- *Service Centers* (material stocking)

  - Domestic -- New Jersey, Michigan, Illinois
  - Foreign -- Japan, England, Germany, Singapore

- *Independent distributors*

- *Authorized agents*

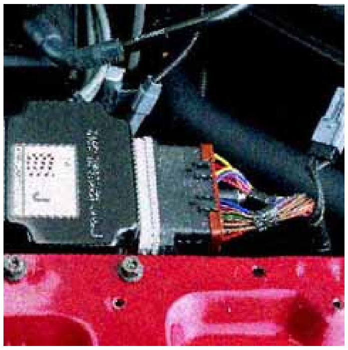
Reprocessor relationships -- Through our relationship with alloy reprocessors we can provide a direct link to special customer needs. The list below describes alloy reprocessors:

- Re-rollers (foil thickness < 0.003 inches [0.08 mm])

- Wire re-drawers (wire diameter < 0.050 inches [1.27 mm])

- Tubing re-drawers (tube diameter < 0.75 inches [19.05 mm])

Industry contacts -- In addition to reprocessor relationships, numerous industry contacts are available for other services. These include:



- plating
- stamping
- welding & brazing
- spring design
- forging
- extrusions (small and large)
- photochemical machining (etching)
- heat treating
- casting
- flexible circuitry / lamination

Technical Exchange

Section V:
Design & Analysis
Finite Element Analysis

Section VI:
Prototype & Verification

Design Guide -
Table of Contents

PROTOTYPE & verification

INDUSTRY TRENDS
▼
CONNECTOR REQUIREMENTS
▼
DESIGN & ANALYSIS ◄ MATERIAL PROPERTIES
▼
PROTOTYPE & VERIFICATION
▼
QUALIFICATION
▼
PRODUCTION

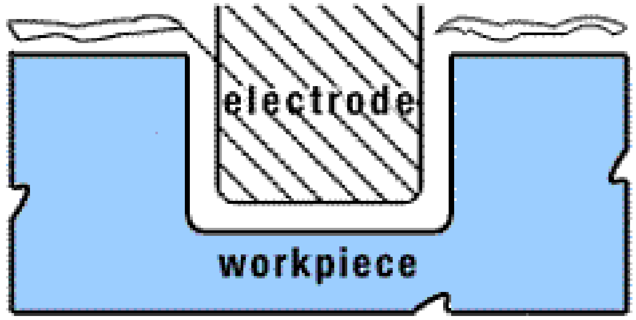
Stamping is a high speed, high volume, low cost process that requires a relatively high initial cost and long lead time for tooling. With shortened development cycles, the need for rapid prototyping and verification is an important requirement. The following section discusses a few prototyping methods.

Methods

EDM -- Electrical Discharge Machining

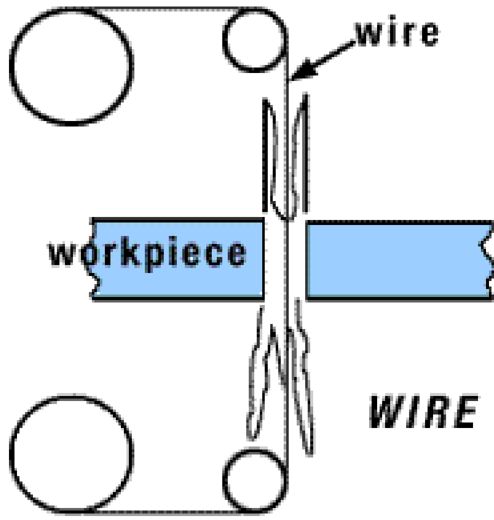
FIGURE 32: ELECTRICAL DISCHARGE MACHINING

Prototype contact quantities are fabricated using EDM. Two types of EDM are conventional (ram) and traveling wire (TW) (Figure 32). Conventional EDM utilizes a copper or graphite electrode configured as the cavity desired in the workpiece. The area of the workpiece, the type of material and the machining conditions determine machining speeds. All EDM applications require a dielectric fluid to act as a spark conductor, a coolant and a flushing medium that carries away swarf. For conventional EDM, the most common dielectric fluid used is light petroleum based oil.



ELECTRODE EDM

Traveling-Wire (TW) EDM utilizes the same principles as conventional EDM, with the fundamental difference that straight sided cuts require a wire electrode. For TW-EDM, brass and copper wire electrodes are the most common. Wire diameters range from 0.002 to 0.012 inches (0.05 to 0.30 mm). Dielectric cooling of the electrode and workpiece usually employs deionized water.



WIRE EDM

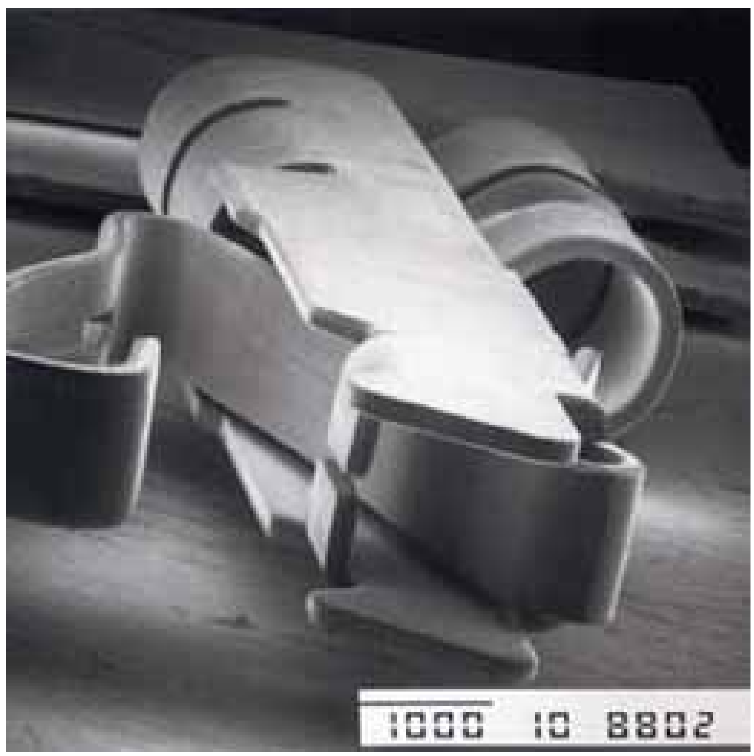
For both conventional and traveling-wire EDM, the machining rates of beryllium copper are typically 20% lower than those of tool steels due to its higher electrical conductivity. The edge condition of the EDM material is dependent upon the conductivity of the material. Some EDM'd edges can be "burned" or annealed which may alter the performance of the sample versus a stamped sample. This is important for prototype samples with small width to thickness (w/t) ratios.

Additional information is available in the Brush Wellman TechBrief "Electrical Discharge Machining Beryllium Copper."

Photo Chemical Machining (Etching)

The copper alloy etching process is either continuous reel-to-reel or flat sheet batch. The material is first coated on both sides with photoresist film that is hot roll laminated in either dry or liquid form. The type of incoming material modifies the preclean and activation step performed before lamination. Following lamination, an ultra-violet (UV) light source exposes the photoresist through the desired pattern using a precision pattern glass or film artwork. The finished pattern develops such that areas to be retained as metal are coated with resist and etched areas are free of resist. The material then runs past a series of nozzles spraying etchant, typically cupric chloride or ferric chloride. The final process step is to strip the protective photoresist from the finished part. The etching rates are dependent upon the isotropy of the etched materials.

Stereo Lithography



Stereo Lithography is a Computer Aided Prototyping (CAP) process that allows a designer to quickly construct a three-dimensional model designed and stored on a CAD system. The process automatically builds complex plastic parts by successively printing cross sections of photopolymer (liquid plastic) on top of each other. The process proceeds joining all of the thin layers to form a whole part. With this technology, the parts grow out of a vat of liquid plastic. The method of fabrication is extremely powerful for quickly reducing design ideas to physical form and for making prototypes. The parts are strictly non-functional in representing the mechanical properties of stamped contacts.

Design evaluation

Design evaluation is a tool to evaluate design alternatives, proposed improvements, cost reduction proposals or determine cause of field problems. The evaluation proceeds prior to qualification to compare connectors and assures the design is adequate to offer a reasonable probability of acceptable performance during qualification testing. A design evaluation consists of the tests in Table 16.

TABLE 16 - DESIGN EVALUATION

Evaluation	Quantity Measured
Construction Analysis	Contact force Insertion/Extraction Force Plating Adhesion Plating Porosity
Metrology	Contact Spacing Housing Dimensions Contact Dimensions Plating Thickness Contact Geometry
Electrical Characterization	Contact Resistance Current Rating or Capacity Dielectric Strength
Assembly Compatibility	Process Thermal Stress Insulation Resistance Solvent Resistance
Safety Approval	UL Flammability

Test methods & data

As mentioned in Section V -- Design & Analysis, FEA models require material property inputs as well as experimental data for correlation. The following data is available from Brush Wellman in the document titled "Atlas of Stress-Strain Curves for Copper Beryllium Strip".

FEA Data -- Yield curve to rupture (paired data) for each of the following alloys and tempers in both the transverse and longitudinal rolling directions are available:

3 AT, HT

160

25 AT, 1/4 HT, 1/2 HT, HT, H,

190 AM, 1/4 HM, 1/2 HM, HM, SHM, XHM, XHMS

165 AM, 1/2 HM, 1/2 HM, HM, XHM

290 TM02, TM04, TM06

174 1/2 HT, HT

Table 17 provides a sample of the paired data available. Here the tensile specimen is 0.008 X 0.250 inches (0.20 X 6.35 mm).

Table 18 contains the Methods used to obtain various types of data:

Additional detailed information on tensile and hardness testing is available in the Brush Wellman TechBriefs "Tensile Testing Beryllium Copper" and "Hardness Testing Beryllium Copper."

TABLE 18 - TEST METHODS

Date Required	Test Method
Tensile Test Properties	ASTM E 8
Hardness (Vickers or DPH)	ASTM E 384
Grain Size	ASTM E 112
Electrical Resistivity	ASTM B 193
Formability	ASTM E 290
Stress Relaxation	ASTM E 328 Part C-3
Solderability	MIL STD 202 Method 208

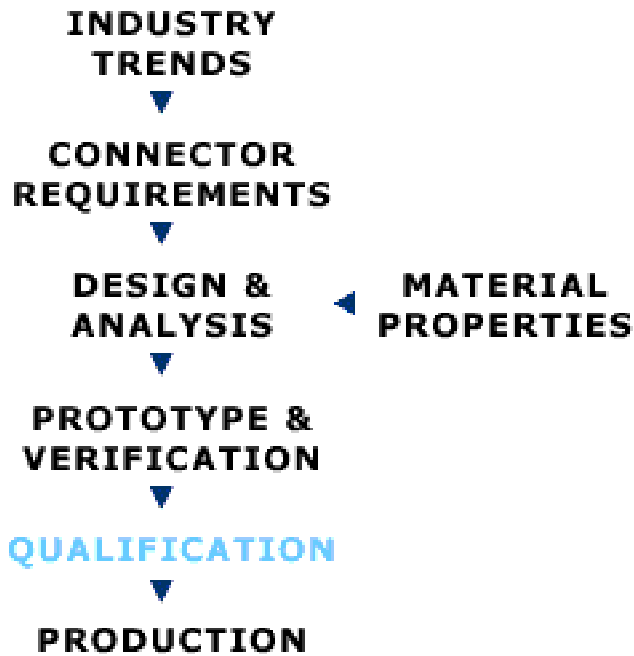
Technical Exchange

Section V:
Design & Analysis
Design Review

Section VII:
Qualification

Design Guide -
Table of Contents

QUALIFICATION



Connector specifications define the recommended stress tests and requirements for connector qualification. This also includes recommended sample sizes for the tests. The specification's purpose is to set a standard for initial qualification of connectors, define tests for requalification or periodic stress testing of on-going production and assess variations in connectors due to changes in design or assembly processes. The electronics industry, automotive industry and the military have documented specifications for connectors used in their applications.

Electronics

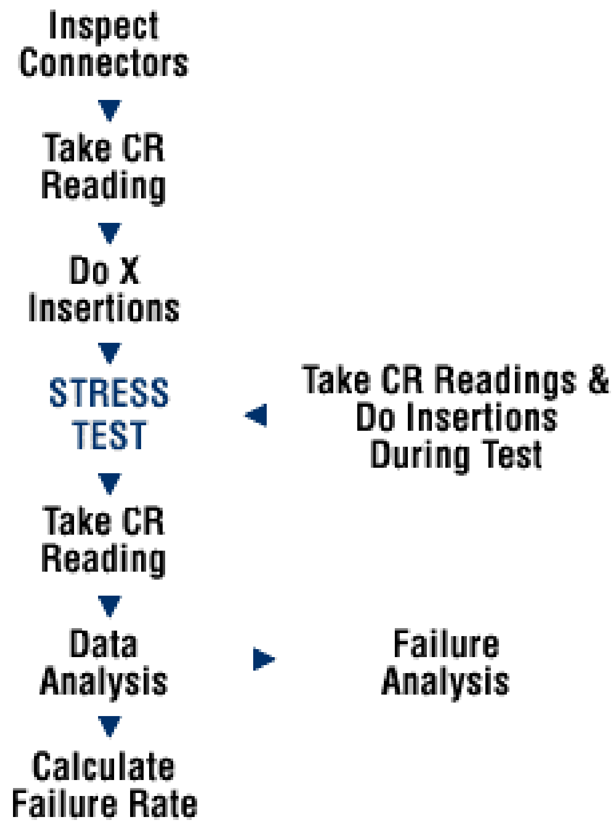
General Requirements

The general requirements of a connector determine the appropriate environmental qualification tests. **Packaging and cleanliness** requirements are to protect the connector from mechanical damage and contamination during shipping and handling. The **operating environment** consists of corrosive gas, particulate and psychrometric (temperature & humidity) conditions. Section III - Environmental Requirements describe these. **Shipping and storage conditions** are the conditions prior to installation.

Environmental Tests

Environmental tests usually consist of accelerated conditions to simulate the lifetime of a connector and/or system and the test results are a measure of the reliability of the system. The criterion to measure whether or not a connector is reliable is a change in contact resistance. A 4-wire probe method measures the contact resistance while negating the effects of bulk resistance in the measurement. Before, during and after aging, the greatest change in resistance (CR) shall be determined for each contact with respect to its initial, acceptable contact resistance reading. A statistical method analyzes the resistance data to determine the connector failure rate or reliability. (Figure 33)

FIGURE 33: STRESS METHOD TEST



In addition to this requirement, connectors must meet a specified minimum number of insertion cycles. Connector test vehicles emulate the actual connector function. The assembly processes for the test vehicles should be representative of the application manufacturing processes. Environmental stress tests are thermal cycling, thermal aging, gaseous testing, temperature and humidity testing, dust sensitivity and vibration and shock testing.

Thermal cycling

This test provides a short term simulation of the long term effects of temperature cycling. The Coffin-Manson relationship for metal fatigue determines the number of cycles required at test temperatures to equate to the number of anticipated cycles at field temperatures. The test consists of a simulated shipping environment followed by an operational environment.

Typical conditions:	Shipping = 5 thermal cycles -40°C to +65°C (-40°F to 150°F) Operational = 100 thermal cycles 0°C to 75°C (32°F to 170°F)

Key material properties are thermal mismatch or CTE (Coefficient of Thermal Expansion).

Thermal aging

This test provides a short term simulation of the long term effects of exposure to elevated temperatures.

Typical conditions: 700 hours at 100°C (212°F)

Key material properties are dry oxidation of base materials and thermal stress relaxation.

Gaseous testing

The purpose of gaseous testing is to provide a short term simulation of exposed contact base metal corrosion. Gold finishes degrade through the ingress of corrosion products from various sources. The Battelle Memorial Institute's Mixed Flowing Gas (MFG) test is an example of this test type. Corrosion migration and pore corrosion are the two degradation mechanisms. The gaseous test involves exposing contacts to corrosive gases during a thermal cycling or aging.

Typical conditions: 25 cycles of thermal cycling with gas concentrations in the part per billion ranges (H_2S, NO_2, Cl_2).

Key material properties are plating integrity (degradation) and shielding effects of the housing.

Pore Corrosion

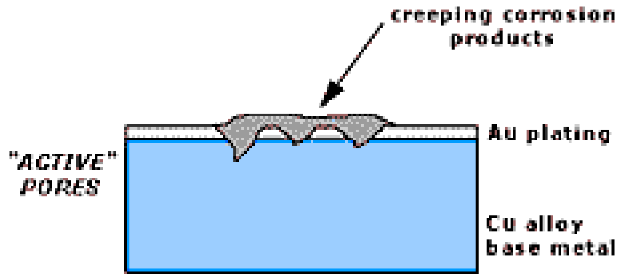
FIGURE 34: PORE CORROSION

The mechanism is corrosion when the defect site is a pore. A pore is a small discontinuity in the contact finish from which corrosion growth occurs (Figure 34).

Corrosion Migration

Corrosion migration refers to the movement of corrosion products into the contact area from sites away from the contact interface.

Such sites include contact edges and defects in the contact finish. Corrosion migration is of concern predominantly in environments in which sulfur and chlorine are present.



Temperature and humidity testing

The purpose of this test is to provide a short term simulation of the long term effects of high

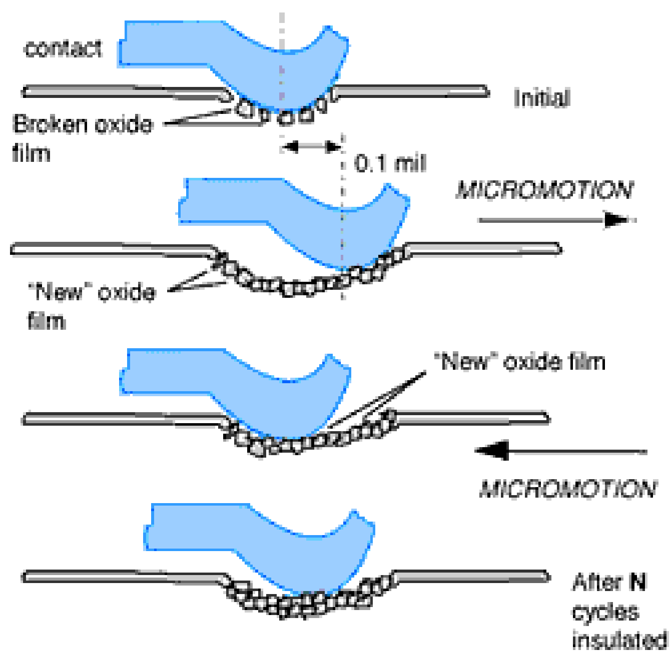
temperature and humidity. Humidity affects galvanic corrosion. Fretting corrosion is the degradation mechanism.

Typical conditions: 300 hours at 50°C (122° F) and 80% relative humidity

Key material properties are wet oxidation of the platings and base materials.

Fretting Corrosion

FIGURE 35: FRETTING CORROSION



Tin is subject to fretting corrosion. Tin is resistant to surface corrosion in that protective oxide film forms on the tin surface that limits further corrosion of the tin. This oxide film does not affect contact resistance since mating of the connector disrupts it. The thin, hard and brittle tin oxide fractures under the application of contact normal force. The soft, ductile tin, flows to enlarge the cracks in the oxide and extrudes through the cracks to establish the desired metallic interface. This mechanism explains the utility of tin finishes in the presence of an oxide. Unfortunately, the oxide forming tendencies of tin remain active, and the if contact interface moves, due to thermal cycling, contact resistance increases. This degradation mechanism is fretting corrosion. Fretting refers to the small motions, hundredths to tenths of a millimeter, which occur randomly due to mechanical disturbances or thermal expansion mismatches. The tin surface reoxidizes during the fretting exposure and is a degradation mechanism causing increases in contact resistance (Figure 35). Contact lubricants and high normal forces prevent micromotion of the contacts and minimize fretting corrosion.

Dust sensitivity test

This test tracks the response of connectors exposed to increasing amounts of dust to determine the point at which performance declines. Contact resistance change or the number of opens that occur is a monitor of performance.

Typical conditions: Dust application in milligrams/square inch

Key material properties are normal force and wipe.

Vibration and shock test

Connector vibration and shock testing are performed at the next level assembly since the input level is very dependent on the mounting structure. The four vibration input types are random, sine-on- random, sine dwells and sine sweep. Operational and shipping conditions are dependent on the levels and packaging of the product. The plane and amplitude of expected shock and vibration affect connector design. A resonantly vibrating member can destroy electrical continuity causing intermittent fails. Vibration tests determine contact resonance at their natural frequencies. A drop table simulates impact during shipping. Here a shock load determines the level that will cause the contacts to separate. Shock load definition is a g-level and duration.

Automotive (USCAR)

The automotive industry specification covers the design verification testing of electrical terminals, connectors and components that constitute the connection systems in 12 volt DC vehicle applications. In addition to thermal shock, temperature and humidity cycling and high temperature exposure, the spec also includes salt fog, soap shower, fluid resistance and immersion tests.

Military (MIL-STD-1344A)

The most commonly used military specification for connectors is MIL-STD-1344A "Test Methods for Electrical Connectors." There are three test classes: environmental (1000 class), mechanical (2000 class) and electrical (3000 class). All Department and Agencies of the Department of Defense approve of this military standard. MIL-STD-1344A is the basis for many of the methods in both the electronics and automotive specifications.

PRODUCTION

INDUSTRY TRENDS
▼
CONNECTOR REQUIREMENTS
▼
DESIGN & ANALYSIS ◄ MATERIAL PROPERTIES
▼
PROTOTYPE & VERIFICATION
▼
QUALIFICATION
▼
PRODUCTION

Copper alloy strip production consists of casting an ingot, hot rolling the ingot to approximately 0.5 inches (12.7 mm) thick, cold rolling to final gage and then slitting to the required width. Various intervals in the cold rolling process require solution annealing thermal treatments, often after reduction, and in some cases after slitting the final gage product. Solution annealing softens the material for further cold working. At later stages of processing, the treatments engender proper temper, strength and formability. Stress relief thermal treatments after slitting reduce residual stresses. The metal surface requires cleaning at various stages of the processing. Benzotriazole (BTA) coats the strip to preserve the final finish.

Stamping uses is a reel-to-reel production line that

features a high speed precision press capable of speeds up to and exceeding 1000 strokes per minute. The press utilizes a progressive stamping die that contains tungsten carbide punches and dies. Feeding the strip into the tool pierces it along both edges.

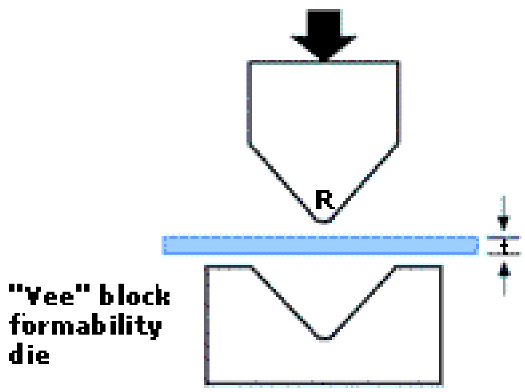
These holes locate the strip precisely as it advances one unit length with each stroke of the press. At each station of the tool, multiple piercings contribute to the final configuration of the product. Plating can also be a reel-to-reel operation. Assembly into plastic housings requires sectioning the plated strip into specified lengths.

PRODUCTION

Fabrication Considerations

Formability

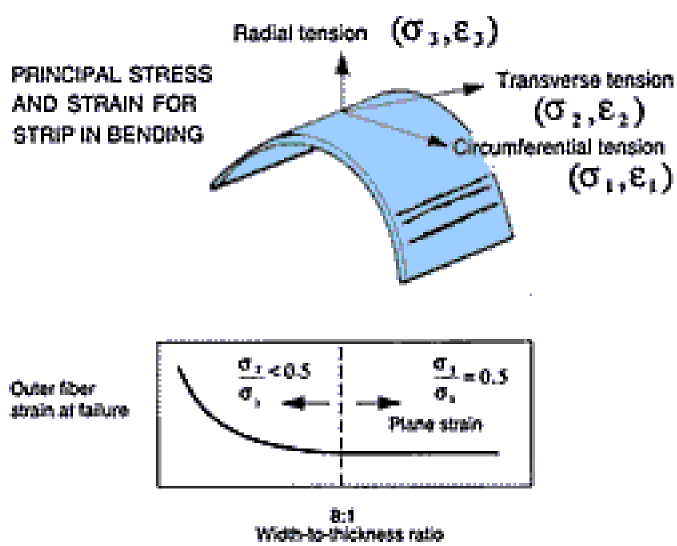
FIGURE 36: VEE BLOCK FORMABILITY DIE



The **formability ratio or R/t** is the ratio of the bend radius *(R)* to the strip thickness *(t)*. This value defines the sharpest forming radius allowable prior to failure. A 90 degree bend test using a "vee" block and die generates formability data (Figure 36). An *R/t* value of 0 defines a material that can form a very sharp bend without failure. Larger *R/t* values indicate reduced formability. Formability is dependent on the material's yield strength and elongation with formability decreasing for higher strength and harder tempers.

The ability to make a sharper bend improves as the strip width decreases at constant thickness. For large width to thickness ratios (≥8), a plane strain state exists producing reproducible and conservative estimates. When width to thickness ratio decreases below 8, the deformation mode changes from plane strain to plane stress. (Figure 37) More localized or necking strain is available to assist forming in the latter before fracture ensues. Thin strip is formable to tighter minimum bend radii than suppliers' published minimum bend ratios.

FIGURE 37: FORMABILITY WITH DEPENDENCE



However, parts formed with this ratio are more sensitive to edge conditions and damage associated with stamping. Additional information is available in the Brush Wellman TechBrief "Formability of Beryllium Copper Strip."

Longitudinal versus transverse forming

The directionality of strip properties is a result of cold rolling. Formability is a function of the bend orientation relative to the rolling direction in a heavily cold rolled product. The formability in the longitudinal direction, good way bending, is usually better than that present in the transverse (bad way) direction (Figure 38).

FIGURE 38: BENDING DIRECTIONS

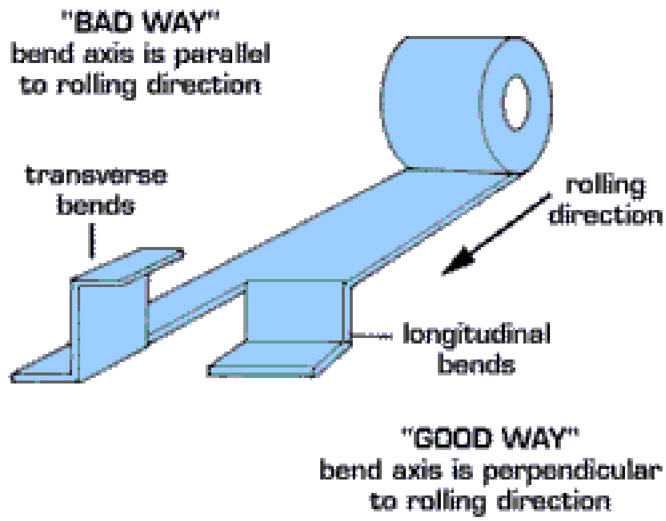


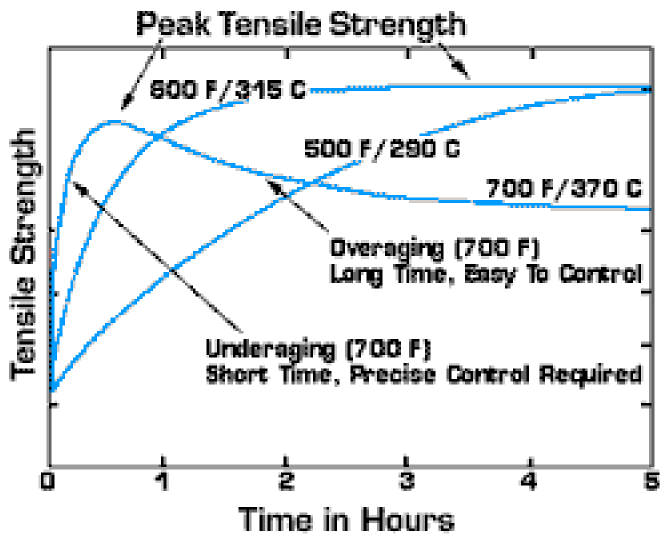
Table 19 presents Formability data for various tempers of contact alloys in the strip thickness range typically specified for connector applications (0.010-0.050 inch or 0.25-1.27 mm).

Heat Treating

Heat treating beryllium copper alloys is a two-step process that consists of solution annealing and precipitation age hardening. Because Brush Wellman performs the required solution anneal on all wrought products prior to shipping, most fabricators' primary concern is the age hardening process for parts to be heat treated after forming. Mill hardened products are age hardened prior to shipment and require no additional heat treatment by the fabricator. During the age hardening process, microscopic, beryllium rich γ-particles form in the metal matrix. This is a diffusion controlled reaction, and the strength will vary with aging time and temperature.

Recommended or "standard" age hardening time and temperature combinations have been determined for each beryllium copper alloy. Standard times and temperatures allow parts to reach peak strength in two to three hours, without strength decrease due to extended temperature exposure. As an example, the Brush Alloy 25 response curves in Figure 39 indicate how low, standard and high aging temperatures affect both peak properties and the time required to reach peak strength.

FIGURE 39: RESPONSE TO AGE HARDENING LOAD CASES (ALLOY 25)



In Figure 39, at the low temperature of 550°F (290°C), the strength of Brush Alloy 25 increases slowly, and peak strength is not reached until approximately 30 hours. At the standard temperature of 600 F (315°C), Brush Alloy 25 exhibits virtually no change in strength after three hours of exposure. At 700°F (370°C), Alloy 25 reaches peak strength in 30 minutes and declines almost immediately. In short, as aging temperature increases, the time necessary to reach peak strength decreases, as does maximum obtainable strength. This response is similar for all beryllium copper alloys, but at different standard temperatures.

Beryllium copper can be age hardened to varying degrees of strength. The term **peak aged** refers to beryllium copper aged to maximum strength. Alloys not aged to maximum strength are **underaged**, and alloys aged beyond maximum strength are **overaged**. Underaging beryllium copper increases toughness, uniform elongation, and fatigue strength. Overaging increases the alloy's electrical and thermal conductivities and dimensional stability. Beryllium copper never ages at room temperature even after storage for significant lengths of time.

Allowable variances in age hardening time are dependent on furnace temperature and final property requirements. To peak age at standard temperature, furnace time control is typically +/- 30 minutes. Avoiding overaging during high temperature aging requires more precise time control. For example, the aging time of alloy 25 at 700° F (370°C) must be controlled to +/- 3 minutes to hold peak properties. Similarly, underaging requires tight control of the process variables because of the sharp initial increase in the aging response curve. In the standard age hardening cycle, heating and cooling rates are not critical. To ensure that aging time does not begin until parts reach temperature, a thermocouple placed on the parts determines when the desired temperature is achieved.

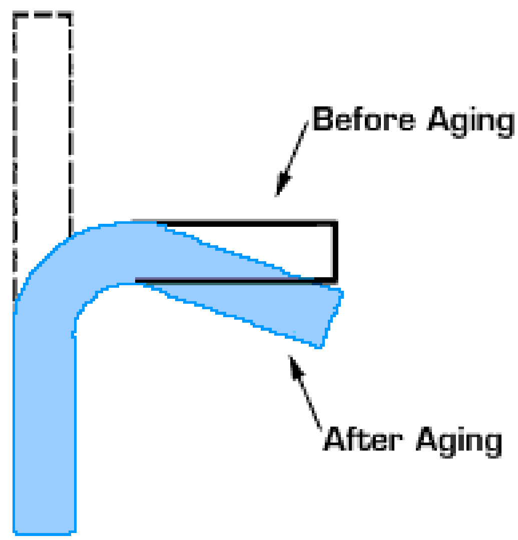
Brush Wellman's "Guide to Beryllium Copper" contain a complete set of aging response curves.

Heat Treatment After Stamping

Shape Distortion occurs during the age hardening of heat treatable tempers of beryllium copper after stamping. Mill hardened beryllium copper is not subject to shape distortion. The cause of aging distortion in small parts is non-uniform residual stresses resulting from mechanical forming operations (Figure 40).
Compressive stresses promote the aging process and tensile stresses inhibit the aging process and accompanying volume changes. the following reduces or eliminates distortion:

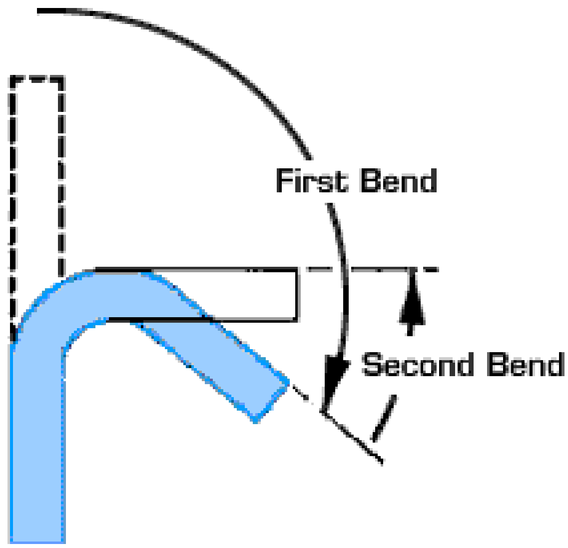
- changing to a mill hardened temper
- selecting the hardest temper that will meet formability requirements
- fixturing during the age hardening process
- eliminating stress in the parts

FIGURE 40: VOLUME CONTRACTION DUE TO AGE HARDENING



- providing uniformity in stress using a two-step bend process (Figure 41)
- increasing the age hardening temperature with decreased time at temperature
- designing the part so that heat treating will move the part into the specified dimension.

FIGURE 41: TWO-STEP BEND PROCESS



Rules of Thumb for heat treating stamped parts:

- To prevent part damage or distortion and also to allow the strip to move when it shrinks requires an interleaf made from stainless steel, or material with a comparable thermal expansion coefficient.
- The material may require coining in the bend area to achieve a repeatable and predictable movement during heat treat.
- Material shrinkage during heat treat requires allowance in the die progression.
- Strip shrinkage requires reel tension control. Spacers may control the winding tension.
- Carrier strip straightness requires heat treat reel diameter consideration. Increasing the reel diameter decreases the bend on the inner windings.

For more detailed information on shape distortion see the Brush Wellman TechBrief "Shape Distortion During Age Hardening of Beryllium Copper Parts."

Heat Treatable versus Mill Hardened

Beryllium copper is available in both heat treatable and mill hardened tempers. Table 20 will discuss the differences to review prior to selecting the proper temper.

FIGURE 42: HEAT TREATED VS. MILL HARDENED LOAD CASES

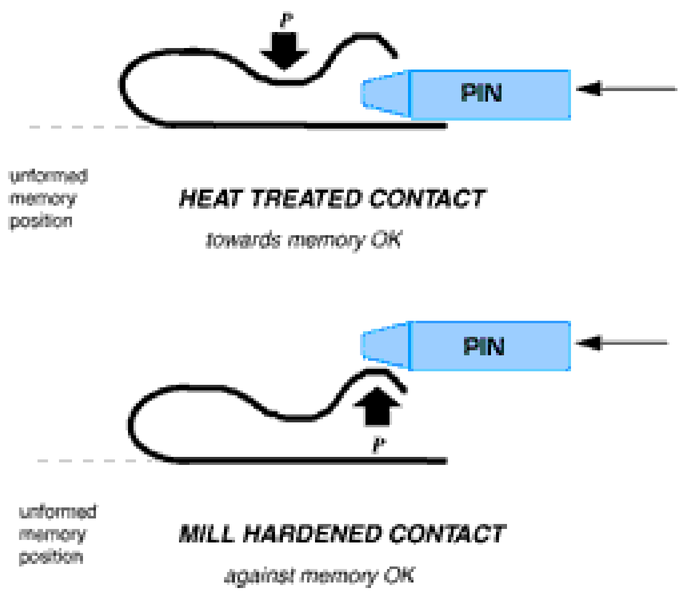


TABLE 20 - HEAT TREATABLE VS. MILL HARDENED		
Property	**Heat Treatable**	**Mill Hardened**
Processing	Rolled, formed, heat treated Best possible formability	Heat treated, rolled, formed
Formability	Formed and then heat treated	Heat treated before forming
Grain Direction	Nearly isotropic properties since heat treating stress relieves rolling	Transverse direction has limited formability for higher tempers
Residual Stress	Responds equally to applied strain regardless of direction	Contains residual rolling stresses. Limited load capacity in unbending direction. (Figure 42)
Stability	Minimal stress relaxation at elevated temperatures	Subject to stress relaxation due to residual stresses
Heat Treatment Distortion	Shrinkage during heat treatment	No shrinkage since formed after heat treatment
Plating	Post plated after heat treatment	Can be plated before or after forming

PRODUCTION

Shape Effects

Die exit camber (edgewise curvature) is the lateral departure of the strip edge from a straight line, which may be unidirectional or reversing. Edge treatment, tension leveling or stress relieving reduces camber.

Flatness is the degree to which a surface of a flat product approaches a plane. Flat strip is preferable with virtually no crown and no oil can or wavy edge. Flatness and straightness are critical to feeding and indexing automated assembly machines. A **heat distortion** test is the method to measure flatness variation caused by internal stress. Samples are prepared parallel and perpendicular to the rolling direction prior to heat treatment. The samples are
heat treated and measured for out-of-plane variation.
Coil set (longitudinal curl) is a unidirectional departure from longitudinal flatness. **Crown** is the variation in thickness from edge to edge and edge to center.

Burrs or edge damage are the thin ridges or roughness left by a cutting operation such as slitting, shearing, blanking or sawing. Extremely localized plastic deformation results from the combination of shearing and fracture. The slit edge geometric features ("roll over," "cut/break ratio" and "burr") are dependent upon material strength, tooling clearances and knife sharpness. Slit edge deformation results in work hardening and residual stress input to a depth of 50-100% of the strip thickness normal to the slit edge. Slit edges exhibit a hardness increase of 10-15% over the base metal hardness (DPH scale).

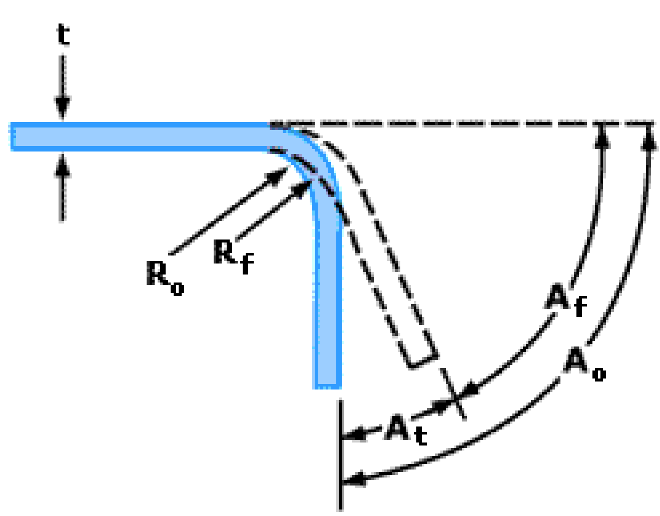
Edge conditioning is effective in relieving slit edge stress, but only by removing edge material to a depth of approximately 100% of the strip thickness. Fine pitch connectors utilize rough **sheared edges** after stamping as contact surfaces. To minimize rough edges, keep tools sharp and punch to die clearance equal to 3% of the stock thickness. Also, 25-50% shear on edge is desirable.

Coining is beneficial where one area requires high strength and another area requires good formability. Coining affects base properties by increasing yield strength (due to work hardening), lowering ductility, degrading bend formability and diminishing stress relaxation resistance. Thermal stress relief will restore the original stress relaxation properties.

Residual stresses are slitting stresses at the slit strip edge that can cause a shift in the x-y position of the contacts during stamping. The residual stress is more important as width to thickness (w/t) ratio decreases. Slit edges exhibit residual stress up to 20% of the 0.2% offset yield strength of the base metal. The method to measure internal stress generated in a stamping die is an **angular distortion test**. Samples are formed to a known angle prior to heat treatment. Following heat treatment, measure the distortion from that angle to determine the level of internal stress.

Other Effects

FIGURE 43: SPRINGBACK OF FORMED STRIP



Springback causes dimensional changes in formed components after release of the forming tool pressure. Overformed bends compensate for springback to maintain the desired part geometry. Springback increases with increasing yield strength and punch radius and with decreasing elastic modulus and strip thickness (Figure 43). The differences in springback do not allow a temper change once tooling is built.

An empirical equation to describe 90° plane strain bend springback, K, for all punch radius/strip thickness ratios is:

$$K = \frac{A_f}{A_o} = -25.54X^3 + 17.91X^2 - 5.85X + 1.08$$

Where X is the dimensionless variable:

$$X = \left(\frac{YS}{E}\right)\left(\frac{R}{t}\right)$$

and:

A_t = formed angle
A_o = bend or die angle (90°)
YS = 0.2% offset yield strength
E = modulus of elasticity
R = punch radius
t = strip thickness

Tolerance effects -- A number of factors contribute to tolerance variations including production related concerns such as tool dimensions, set-up, materials, operator, environment. Also design related effects such as material width, thickness, length, contact gap and alignment contribute.

Surface roughness -- An indication of surface irregularity measured by the root-mean-square (RMS) of the surface variations. Typical values for commercial spring material prior to plating are 4-8 RMS.

Cleaning

During aging, the beryllium copper alloys develop a surface oxide composed of beryllium oxide and, depending on the alloy and furnace atmosphere, copper oxides. These oxide films vary in thickness and composition and are often transparent. In a typical age hardening heat treatment (2 hours at 600°F [316°C]) in an "inert" atmosphere, expect a film thickness of about 1.2 µinches (300 angstroms) on alloy C17200. Under solution annealing conditions (1450° F [788°C]), the film can reach as much as 12-50 µinches (1000-1200 angstroms).

Even a pure hydrogen atmosphere or a hard vacuum cannot suppress surface oxidation of beryllium during age hardening. However, some atmospheres can minimize the copper oxidation. Air atmospheres contribute the most to surface oxide and reducing atmospheres the least. The oxide film must first be removed in order to plate, braze, or solder parts.

The component manufacturer frequently age hardens the beryllium copper after stamping and must clean the parts before subsequent processing. There are many acid combinations which can be used, but those proven most successful in removing films containing beryllium oxide are sulfuric/peroxide (20% H_2SO_4, 3% H_2O_2, 125°F [52°C]) and phosphoric/nitric/acetic (PNA) (38% H_3PO_4, 2% HNO_3, 60% acetic acid, 160°F [71°C]). Nitric acid alone does not do an adequate job of removing beryllium oxide films unless these films are pretreated in hot, concentrated caustic (50-60% NaOH, 265°F [129°C]).

Following is a note of caution when dealing with any copper alloy containing lead, such as Alloy M25 (C17300). Use Nitric acid or PNA rather than a sulfuric acid system because of the insolubility of lead sulfate. Following alkaline cleaning, a preplating acid dip for leaded alloys is fluoboric acid (10-25% at room temperature). A cyanide copper strike is a cleaning and activating step essential for plating leaded alloys.

Additional detailed information is available in the Brush Wellman TechBrief "Cleaning Beryllium Copper."

Soldering

As with most copper alloys, beryllium copper is easily solderable using readily available solder materials. A sound, reliable solder joint requires proper techniques in surface preparation, materials selection, the soldering process and post solder cleaning. Soldering will not affect beryllium copper's properties.

Surface impurities such as oil, grease, dust, stain inhibitors, tarnish and oxide account for a major share of soldering problems. Flux is **not** a substitute for adequate surface preparation and will not reliably remove all surface contamination. Conventional cleaning methods, such as organic solvents, vapor degreasing and alkaline cleaners, are usually adequate for removing dirt, oil and grease. Ultrasonic agitation enhances these cleaning agents. Rinse all cleaning solutions from all surfaces after use.

Conventional techniques remove the black or reddish oxides of copper when present. Transparent, tenacious and refractory, beryllium oxide, as thin as 2 µ inches (500 angstroms), can lead to soldering difficulty. Acid pickling removes oxides formed during heat treatment of beryllium copper.

Solder beryllium copper parts as soon as possible after cleaning. If delays are unavoidable, store the parts in a clean, dry, protected area away from shop dust, acid and sulfurous or ammonia fumes.

Soldering beryllium copper presents no special flux selection problems. As a rule, use the mildest flux that will do the job. Classification of non-corrosive (rosin) fluxes are non-activated (R), mildly activated (RMA), and fully activated (RA). The main advantage of rosin based fluxes are that they become active only with heating. The most frequently used fluxes in soldering beryllium copper alloys are RMA and RA. Hot or warm water rinsing will remove any flux residue.

When soldering beryllium copper to other metals, it is often the other metal that establishes the soldering parameters. The high thermal conductivity of beryllium copper is a consideration when soldering to lower conductivity metals. To concentrate heat at the joint may require heat sinks. Additional detailed information is available in the Brush Wellman TechBrief "Soldering Beryllium Copper."

Solderability

The solder dip test method listed in Table 18 quantifies solderability. Surface cleanliness is the most important material characteristic. Copper can interdiffuse with tin (Sn) to form Cu_3Sn or Cu_2Sn compounds with some copper enrichment ahead of the intermetallic. The environment will determine the stability of the intermetallic phase or Cu-rich phase ahead of it when either grows to reach the surface.

Machinability

The machinability of a given alloy depends on such factors as the operation type, tool life, tooling and tool geometry. A general machinability rating provides the designer with rough machinability guidelines for the available alloys (Table 21).

TABLE 21 - MACHINABILITY RATING

Alloy	**Machinability Rating (Free Machining Brass = 100)**
25	35
M25	40
3	25
510	20
521	20
534	45
654	30
1915	75

As shown, the machinability of beryllium copper Alloy 25 and Alloy M25 are nearly equivalent and they are approximately double the machinability of most competitive alloys. Alloy M25 is a high strength beryllium copper alloy (C17300) developed specifically for automatic screw machine operations. The alloy's composition is the same as that for

Alloy 25, with the addition of 0.3% lead (Pb) to facilitate discontinuous chip formation during machining. The mechanical properties of Alloy 25 and M25 are equivalent.

Alloy 1915 is a heat treatable leaded copper alloy specifically designed for screw machine applications. Brush 1915 alloy is available in rod or wire in diameters ranging from 0.050 inch (1.27 mm) to 0.500 inch (12.7 mm).

Additional detailed machining information is available in the Brush Wellman publication "Machining Beryllium Copper."

Technical Exchange

Section VIII: Production - Fabrication Considerations

Section VIII: Production - Rod & Wire

Design Guide - Table of Contents

PRODUCTION

Rod and Wire

In applications involving miniature and subminiature circular connectors, sockets and coaxial connectors, the process of alloy specification is not significantly different. Here, the nature of the finished contact forces the designer to work with the specified alloy in rod or wire. In addition, the tempers available in the rod and wire product forms vary significantly from those found with strip products (Table 4). Wire is available in coil form and rod is available in straight lengths. Wire is also available in cross sections other than round. The following table lists the mechanical properties of wire for diameters above 0.050 inch (1.27 mm). For diameters less than 0.050 inch (1.27 mm) contact the wire supplier for properties.

Rod Properties

(See Table 22)

Wire Properties

(See Table 23)

As shown, the specific properties of the various alloys do not change significantly in the transition from strip to rod and wire form. The differences in mechanical properties are a result of the wire drawing process itself. The only exception in the specification process is the fact that the designer must evaluate the alloy's machinability rather than formability.

Wire vs. strip

In certain instances wire and/or flat wire are used instead of strip to produce spring contacts. To produce flat wire to the desired thickness, the appropriate diameter round wire feeds through a rolling mill, for flattening. A set of opposing rolls in the perpendicular direction achieves the correct width and forms the edge, whether round, square, or some special shape. Wire with a width to thickness ratio of greater than 3 to 1. is called flat wire.

Selection Guide:

1. **Width** -- Most wire mills cannot produce flat wire widths greater than 0.750-0.875 inches (19.1-22.2 mm). This is because of the maximum "spreading" achievable from wire. For anything wider, slit strip is usually the better option. The cost advantages of wire are most apparent at widths less than 0.150 inches (3.81 mm).

2. **Thickness** -- A strip mill can roll foil gauges down to 0.001 inch (0.025 mm). The limit on wire mills is also 0.001 inch (0.025 mm). For gauges less than 0.001 inch (0.025 mm) contact the wire supplier.

3. **Tolerances** -- Strip will provide closer gauge tolerances up to 0.050 inch (1.27 mm), and flat wire also has good gauge tolerances below 0.050 inch (1.27 mm). Flat wire has tighter width tolerances than strip. Typical wire width tolerances are +/- 0.0003 inch (0.008 mm). Width tolerances are not as tight on round edge wire as flat wire.

4. **Continuous unwelded length** -- Compared to strip, flat wire is available in longer continuous lengths without welds. Flat wire must be supplied on traverse wound coils.

5. **Edges** -- Strip coming off a slitter will have a burr along both edges caused by the shearing action of the knives. Rounding or squaring the edges removes the burr. This does not temper or work harden the edge. However, it incurs an additional cost, and the operation can be time-consuming for large quantities. On a wire mill, rolling creates a smooth, uniform edge for the entire length. For smaller diameter wire, the corner allowance becomes more important. At gauges

above 0.010 inch (0.25 mm), the corner allowance specifies 0.003 inch (0.08 mm) whereas below 0.010 inch (0.25 mm) gauge a rounded corner is standard.

6. **Width-to-thickness ratio** -- As the ratio between width and thickness narrows to 5 or 6 to 1 and below, it can become more difficult to maintain camber, flatness, and other shape parameters when slitting strip. On a wire mill, it is possible to get the ratio down to 1 to 1 that is a square cross section and as high as 30:1 for flat wire.

7. **Tooling --** Knives for slitters and carbide rolls for wire mills are readily available and changeable. In most applications, the major issue is the burr created during slitting. If the condition of the edges is not important, slit strip may be the better choice. When it is a factor, the choice comes down to the cost of slitting and deburring or edge conditioning versus the cost of flat wire. The cost of flat wire is typically 30-50% greater than that of strip.

Brush Wellman supplies wire in diameters from 0.500 inch (12.7 mm) down to 0.050 inch (1.27 mm) with tolerances listed in Section V -- Design & Analysis of this guide. Any one of a number of beryllium copper wire redrawers supply finer wire.

Cost

The proper way to analyze material cost is to examine the value of the metal and its properties versus the overall cost and performance of the connector. A method of performing this analysis is to evaluate the material cost in dollars per pound versus the overall connector cost per X contacts. In a typical connector the cost components are the cost of the base metal, stamping, plating, housing and assembly. Following is a typical cost breakdown for a precious metal plated connector:

Contacts (base metal & stamping) 10-30%

Gold plating 20-30%

Housing / hardware 10-25%

Labor 10-20%

Overhead 25-35%

In addition, scrap value and material quality should factor into the equation when determining manufacturing costs.

Quality Functions

Quality Philosophy

Brush Wellman is committed to our customers' success. Accordingly, we recognize the need to provide high quality products and services as a condition of doing business. The markets we serve include some of the most demanding in the world when it comes to quality of systems, products, distribution and services. We have long been recognized for our quality, excellence and leadership by these highly demanding markets.

We base our quality initiatives on the philosophy of defect prevention and variability reduction. We focus on continuous process improvement and make extensive use of statistical tools. We believe that continuous improvement requires employee involvement and teamwork. To maintain high standards of quality, we provide ongoing training in the quality tools to all employees.

Quality statement

"We are dedicated to excellence in customer satisfaction by providing superior products and services."

The Elmore, Ohio facility is responsible for the primary processing of strip product. The Reading, Pennsylvania facility performs the finishing operations. The final location prior to customer shipment is a Service Center. All of these Brush Wellman facilities function under the **BRUSH PRIDE** continuous improvement process that incorporates the fundamentals of the following:

- Just-In-Time Manufacturing
- Total Employee Involvement
- Total Quality Management

- Dedication to Customer Satisfaction

Through implementation of the **BRUSH PRIDE** process in the areas of design, conformance and performance; defect elimination, cost reduction, cycle time reduction and increased customer satisfaction are achieved.

Statistical Process Control (SPC)

SPC is a statistical procedure for catching or detecting variations in production caused by operators, machinery and extraneous factors. Brush Wellman is committed to SPC for monitoring critical product and process characteristics. Prior to implementing new SPC applications on process characteristics, the appropriate procedures are reviewed for completeness. A **Failure Mode Effects Analysis (FMEA)** identifies the key process characteristics. Analysis of historical data determines if the process is under control and normally distributed. After meeting these criteria, a process SPC chart is implemented.

Conformance with process specifications as well as customer specifications is attainable through lot to lot consistency. Melt composition (chemistry), mechanical properties (tensile and yield strength, elongation, hardness), grain size, conductivity, gauge and surface finish are tracked and controlled. Attribute and variable control charts monitor the processes. Each order is traceable back to a heat number.

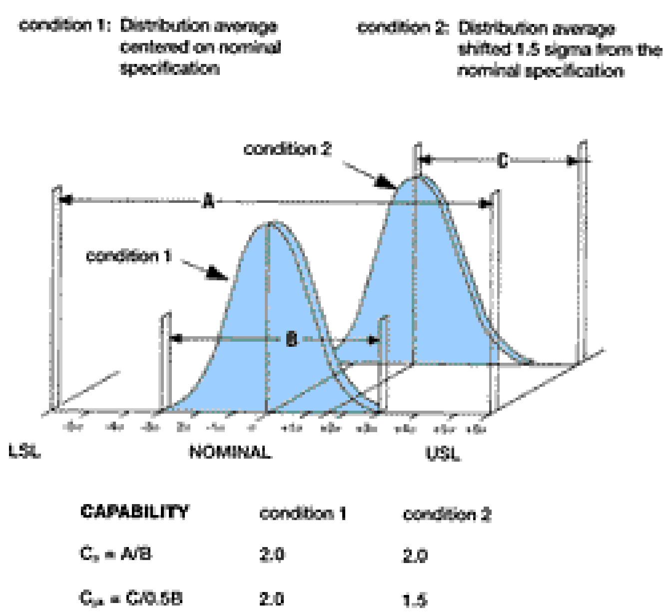
Process Potential, C_p

The process potential of an actual or postulated manufacturing parameter only considers the process spread in relation to the allowable engineering specification spread (Figure 44).

$$C_p = \frac{USL - LSL}{6\sigma} \quad \text{(Bilateral case)}$$

$$C_p = \frac{USL - \mu}{3\sigma} \quad \text{(Unilateral case)}$$

FIGURE 44: CONCEPTS UNDERLYING C_p AND C_{pk}



$$C_p = \frac{\mu - LSL}{3\sigma} \text{ (Unilateral case)}$$

Where:

USL = Upper Specification Limit

LSL = Lower Specification Limit

σ = standard deviation

μ = mean

Process Capability Index, C_{pk}

This index measures the ability of a process to produce product within specification. The capability index measures the degree of centering of the actual process spread with respect to the allowable spread.

$$C_{pk} = C_p (1 - \kappa)$$

Where:

$$\kappa = \frac{|\ Nominal - \mu\ |}{(\ USL - LSL\ ) / 2}$$

Continuous Improvement Process

ISO 9002/QS 9000 Certifications

The Reading, PA plant became ISO 9002 certified in mid-1993 and QS 9000 certified in 1996 and the Elmore, OH plant became ISO 9002 certified in mid-1994 and QS 9000 certified in 1999. The Quality Operating System (QOS) monitors internal and external product performance along with the implementation of the quality system. Overall performance tracking and monthly reviews utilize measurements developed by the management teams at each plant.

ISO/IEC Guide 25-1990

The Elmore Plant Chemical Analysis and Reading Plant Production Mechanical Testing Laboratories have received accreditation to ISO/IEC Guide 25-1990 by the American Association of Laboratory Accreditation (A2LA). The requirements of Guide 25 include and go beyond the relevant requirements of ISO 9002. Some of the additional requirements are as follows:

- Laboratory Quality Manual
- Determination of the Best Test Method
- Measurement systems for gage repeatability and reproducibility studies
- Calibration control
- Training procedures that insure operator competency
- Purchase and maintenance records on the major item of equipment

To provide evidence of our quality, we:

1. Provide material certifications which report test results demonstrating compliance to customer specifications.

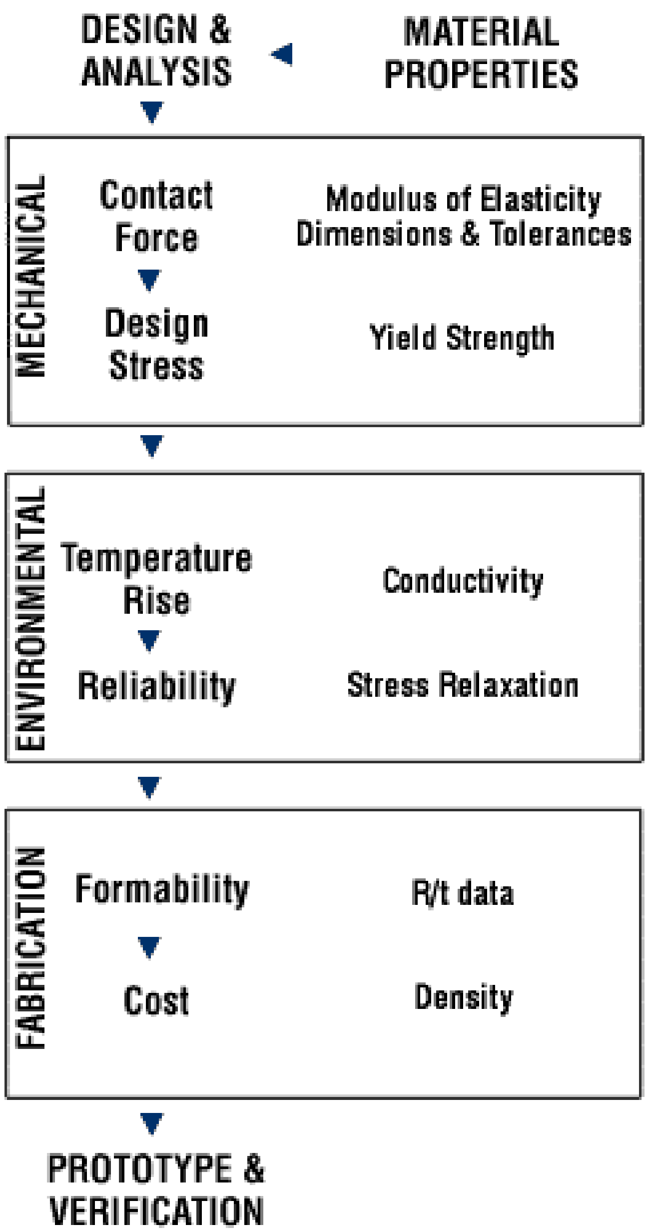
2. On request, will provide detail of statistical process capability and product quality

3. Encourage visits to our operating facilities for the purpose of auditing our quality systems.

APPLICATIONS

Design Exercise

This exercise will walk through a typical connector design utilizing the process flowchart discussed earlier. Design decisions are never one dimensional. The first step is to identify the critical design criteria for each application. The second step is basing the material selection decision on those criteria. The simplified flowchart in Figure 45 illustrates a typical design process.



Mechanical Criteria

The first criteria in the design of a contact are the mechanical properties, namely contact force and design stress. A "gas tight" interface requires adequate normal force to provide and maintain electrical contact. A contact should achieve the normal force without excessive stress during normal operation.

Contact Force

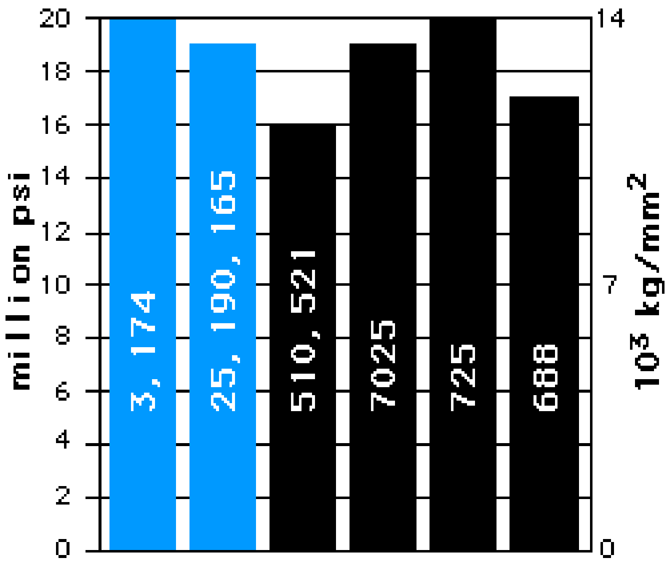
Using the following equation, the contact or normal force of a cantilever beam connector is determined from the physical dimensions of the contact (beam length, *l*, width, *w* and thickness, *t*), the physical movement of the contact (deflection, *d*) and the stiffness of the material (modulus of elasticity, *E*).

$$\text{Normal Force, } P = \frac{d\,E\,w\,t^3}{4\,l^3}$$

The beam length and thickness are most important since they are cubic functions in the equation.

The critical material property here is the modulus of elasticity and the range of values for high performance spring alloys is from 16 to 20 million psi (11.3 to 14.0 x 10^3 kg/mm^2). The modulus is independent of temper. Given that the beam dimensions and deflection remain constant, the modulus can account for a contact force variation of +/- 11%. However, if the contact design uses a modulus of 16 million psi (11,300 kg/mm^2) to achieve the desired contact force, a contact redesign for a smaller beam volume utilizes a higher modulus

CHART 1: MODULUS OF ELASTICITY



material.

Chart 1 shows the modulus of elasticity of several contact materials.

Design Stress versus Yield Strength

A number of methods can calculate the design or working stress. The simplest method uses cantilever beam equations and assumes the maximum surface stress corresponds to the working or design stress as shown in the following equation.

$$\sigma_{max} = \frac{3\,d\,E\,t}{2\,l^2}$$

Where: d = deflection of the beam at the load

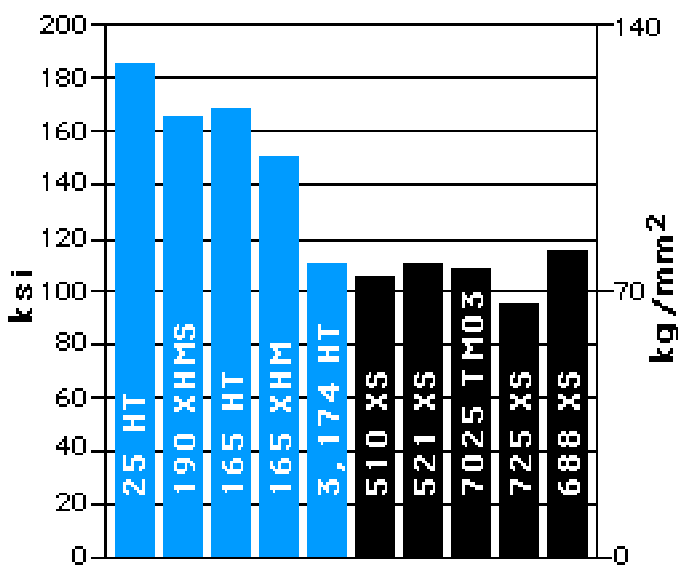
E = Modulus of Elasticity

t = beam thickness

l = beam length

Another method is to use Finite Element Modeling to arrive at a design stress via Von Mises stresses. Both of the stresses are calculable using the nominal or worse case contact deflection. In both cases it is desirable to have a design stress below the yield strength of the spring material to provide a safety factor. If the design stress exceeds the yield strength of the

CHART 2: MAXIMUM YIELD STRENGTH



material, plastic deformation, also known as permanent set, will occur. In cases where entering into the plastic regime of the material is unavoidable, it is advantageous to use a material that is resistant to permanent set. Age hardenable materials are more resistant to permanent set in that they do not rely solely on cold work to provide their strength.

Chart 2 displays the maximum yield strengths of several contact materials.

Thermal -- Electrical -- Environmental Criteria

After determining the contact force and design stress, it is important to analyze the other connector constraints due to electrical and thermal and environmental requirements. Under these circumstances, the most critical connector material requirement is its current carrying capability. Here, the electrical conductivity has a direct impact on the connector resistance and therefore its reliability.

Temperature Rise

The temperature rise in a contact material depends upon the current flowing in the material, the physical dimensions of the contact (beam length and cross sectional area) and the electrical and thermal conductivity. The following equation approximates temperature rise:

$$\Delta T = \frac{J^2 L^2}{2 \gamma_e \kappa A^2}$$

where ΔT is the temperature rise (°F), J is the current (amps), L is the beam length (in), A is the cross-sectional area (in^2), γ_e is the electrical conductivity and κ is the thermal conductivity. In order to be useful, the data requires conversion into compatible units for this equation. Convert electrical conductivity in (%IACS) to amps/volt-in by multiplying by 14700. Thermal conductivity must be converted to volts-amps/inch-°F by multiplying BTU/ft·hr·F by 0.0244.

This resistive or joule heating can result in connector degradation. A typical design criteria is to have the temperature rise less than 30°C for a given current load.

CHART 3: ELECTRICAL CONDUCTIVITY

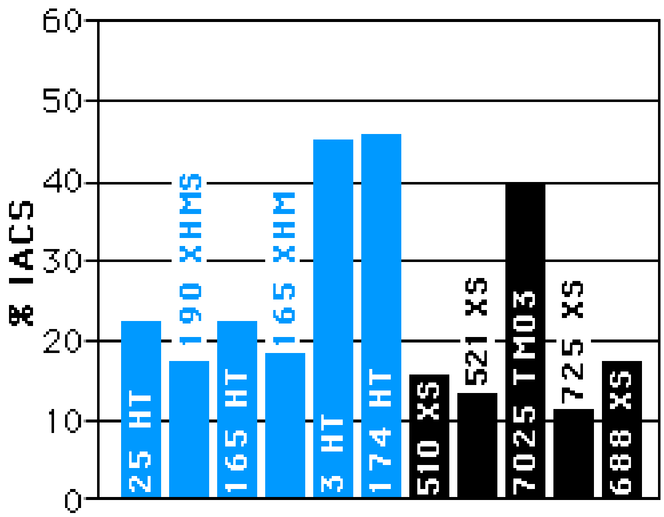
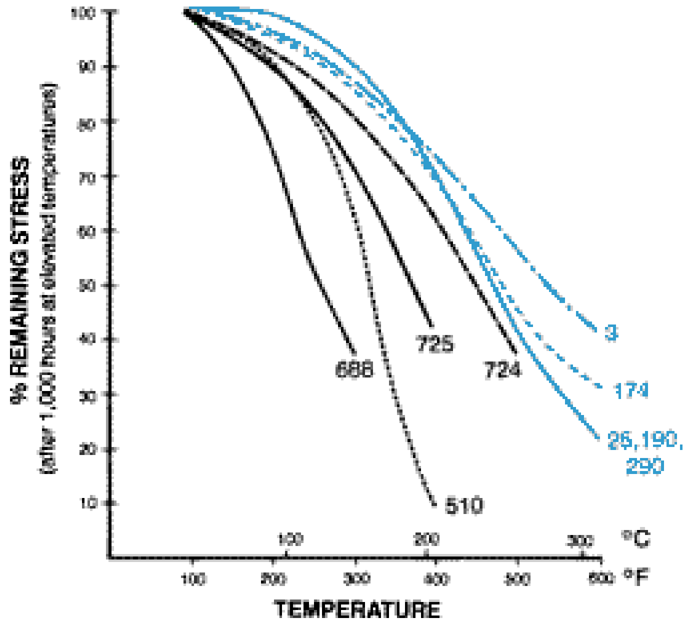


Chart 3 shows the electrical and thermal conductivity products of several contact materials.

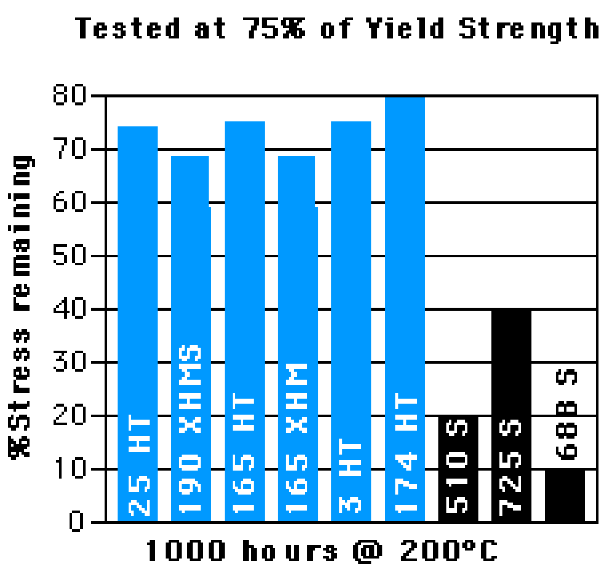
Stress Relaxation

FIGURE 46: EFFECT OF TEMPERATURE ON STRESS RELAXATION



Consider the ambient heating due to the environment as a corollary to the rise in temperature due to resistive heating. Combining these is a worse case scenario for a connector. The elevated temperature conditions have a large impact on the mechanical properties of the connector. The contact force may degrade due to this temperature exposure. Degradation of a connector's normal force may have a direct impact on its reliability if the value drops below the critical requirement for a stable contact system. When choosing a material it is critical to select a material that will provide adequate normal force at the end of its operating life based on the conditions under which it will function. Figure 46 shows a plot of the thermal relaxation characteristics of several spring contact materials. Chart 4 compares stress relaxation characteristics of various copper based alloys tested at 200°C.

CHART 4: STRESS RELAXATION



Fabrication Criteria

While the connector is being designed to achieve the mechanical requirements of normal force and design stress, the manufacturing aspects must not be ignored. Two critical areas require addressing. The first is forming the contact to the correct geometry to meet the part drawing that achieves the mechanical requirements. The second is manufacturing the contact to the specification in a cost effective manner.

Formability

Deciding the formability of the contact addresses a number of questions. Will the contact require stamping or machining? If stamping, what will the stamping progression be and what are the parameters? The most commonly used criterion for forming is the ratio of minimum bend radius divided by the thickness of the strip (R/t). This data is available for most connector alloy materials in both the longitudinal and transverse directions. Checking the part dimensions verifies the critical bend radii of the part and their compliance with the material property. The formability data (R/t ratio) of several connector alloys is in Charts 5a & 5b.

CHART 5A: LONGITUDINAL FORMABILITY

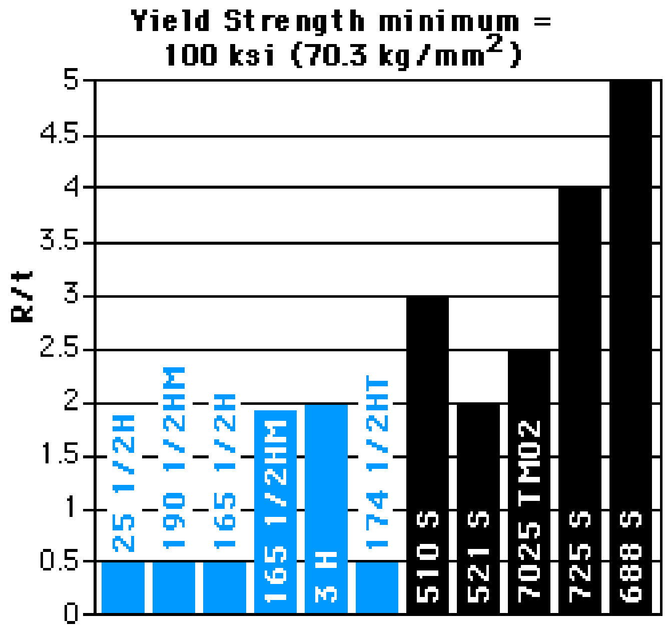
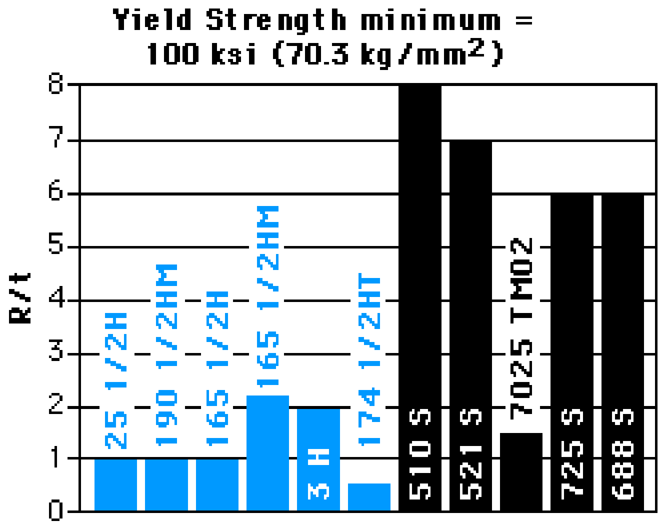


CHART 5B: TRANSVERSE FORMABILITY



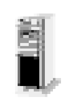
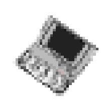
Cost

Several components comprise the connector cost. Included are the base materials, the stamping or machining costs, the plating costs, the thermoplastic housing costs and lastly the assembly costs. In addition, secondary operations, such as heat treating, inherent in the use of an age hardenable alloy, can greatly affect processing costs. On the other hand, mill hardened tempers may provide sufficient strength and formability with no subsequent heat treatment and cleaning costs.

Miniaturization

The industry trend of miniaturization drives smaller centerline spacing, tighter tolerances and lower profile connectors (Table 24). Miniaturization of a standard cantilever beam type contact to one half its existing size is an example of the benefits of using beryllium copper to design smaller contacts (Figure 47).

TABLE 24 - MINIATURIZATION

Product Evolution	**Then** 	**Now** 
Grid	≥0.100" (2.54 mm)	≤0.050" (1.27 mm)
Post Size	0.025" (0.635 mm)	0.015" (0.381 mm)
Material Thickness	0.010 - 0.015" (0.259 - 0.381 mm)	0.003 - 0.010" (0.08 - 0.254 mm)
Contact Force	≥100 grams (1 N)	≤50 grams (0.5 N)

The current design parameters are:

Contact material = phosphor bronze A C51000 (spring temper)

Modulus of elasticity, $E = 16 \times 10^6$ psi (11,300 kg/mm^2)

Yield strength, YS = 100,000 psi (70.3 kg/mm^2)

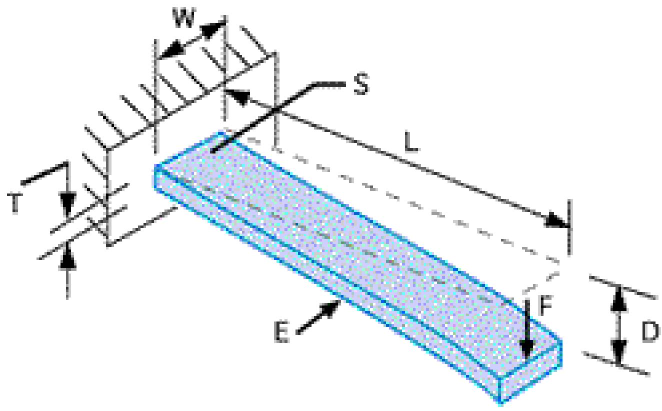
Beam length, l = 0.150 inches (3.8 mm)

Beam width, w = 0.040 inches (1.0 mm)

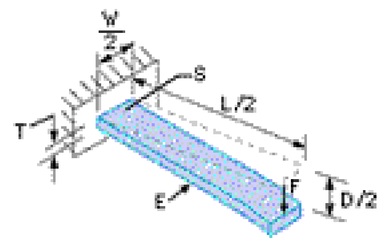
Beam thickness, t = 0.010 inches (0.25 mm)

Deflection, d = 0.007 inches (0.18 mm)

FIGURE 47: MINIATURIZATION



Original design



Miniaturized design

The normal force was calculated using the following equation

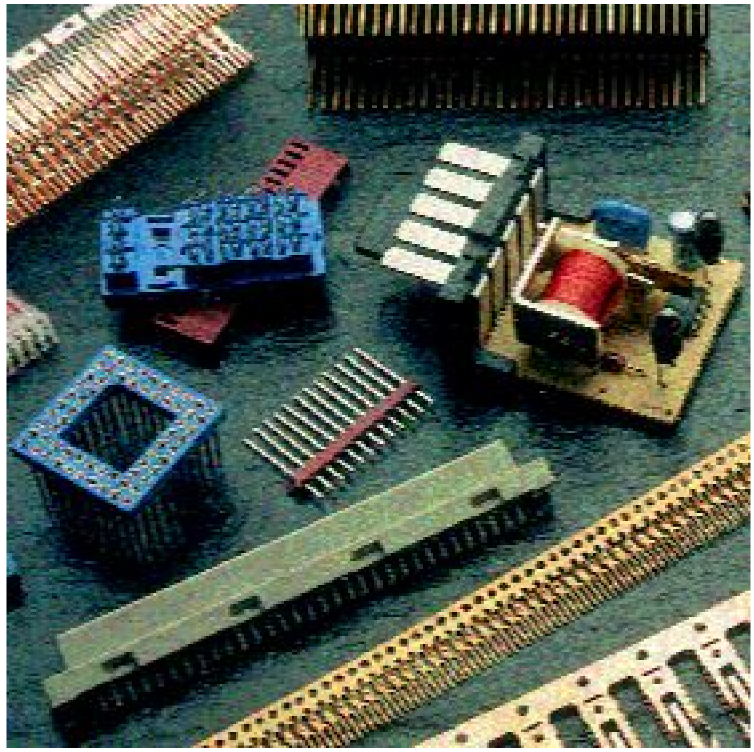
$$\text{Normal Force, } P = \frac{d\,E\,w\,t^3}{4\,l^3}$$

and was found to be 150 grams (1.47 N). This design point achieves a reliable connection for this fictitious application. The next parameter to determine is the design stress. The following equation calculates design stress:

$$\sigma_{max} = \frac{3\,d\,E\,t}{2\,l^2}$$

The design stress is 75,000 psi (52.7 kg/mm^2) which is below the 0.2% yield strength of 100,000 psi (70.3 kg/mm^2) and is therefore acceptable.

The new design will be one half the size of the original design and the dimensions are:



Contact material = phosphor bronze A C51000 (spring temper)

Modulus of elasticity, $E = 16 \times 10^{6}$ psi (11,300 kg/mm^2)

Yield strength, YS = 100,000 psi (70.3 kg/mm^2)

Beam length, l = 0.075 inches (1.9 mm)

Beam width, w = 0.020 inches (0.5 mm)

Beam thickness, t = 0.008 inches (0.2 mm)

Deflection, d = 0.0035 inches (0.09 mm)

Here the normal force is constant as required for a reliable connection and the other dimensions downsize accordingly.

The design stress using the formula previously mentioned with the changed dimensions is 120,000 psi (84.4 kg/mm^2). The design stress now exceeds the yield strength of the material and is unacceptable. The high design stress requires a material with a higher yield strength. The new material chosen is Alloy 25 (C17200) with 1/2 HT temper. The critical parameters for this alloy are:

Contact material = beryllium copper Alloy 25 (C17200) -- 1/2 HT temper

Modulus of elasticity, E = 19 x 10^6 psi (13,500 kg/mm^2)

Yield strength, YS = 180,000 psi (126.6 kg/mm^2)

Beam length, l = 0.075 inches (1.9 mm)

Beam width, w = 0.020 inches (0.5 mm)

Beam thickness, t = 0.008 inches (0.2 mm)

Deflection, d = 0.0035 inches (0.09 mm)

BeCu ADVANTAGE

HIGH YIELD STRENGTH	▶	DESIGN STRESS
HIGH CONDUCTIVITY	▶	CURRENT CAPACITY
STRESS RELAXATION	▶	RELIABILITY
HIGH TOUGHNESS	▶	PERMANENT SET
FORMABILITY	▶	FABRICATION

Recalculating the design stress using beryllium copper is 140,000 psi (98.9 kg/mm^2) which is well below the yield strength of the material that is 180,000 psi (126.6 kg/mm^2). The normal force is now 183 grams (1795 N). To further emphasize the economy of beryllium copper, a thickness reduction to 0.0075 inches (0.2 mm) lowers the normal force back to the design point of 150 grams (1471 N). This thickness reduction lowers design stress to 133,000 psi (93.5 kg/mm^2).

Technical Exchange

Section VIII: Production - Rod & Wire

Appendix

Design Guide - Table of Contents

FIGURE 45: DESIGN EXAMPLE FLOWCHART

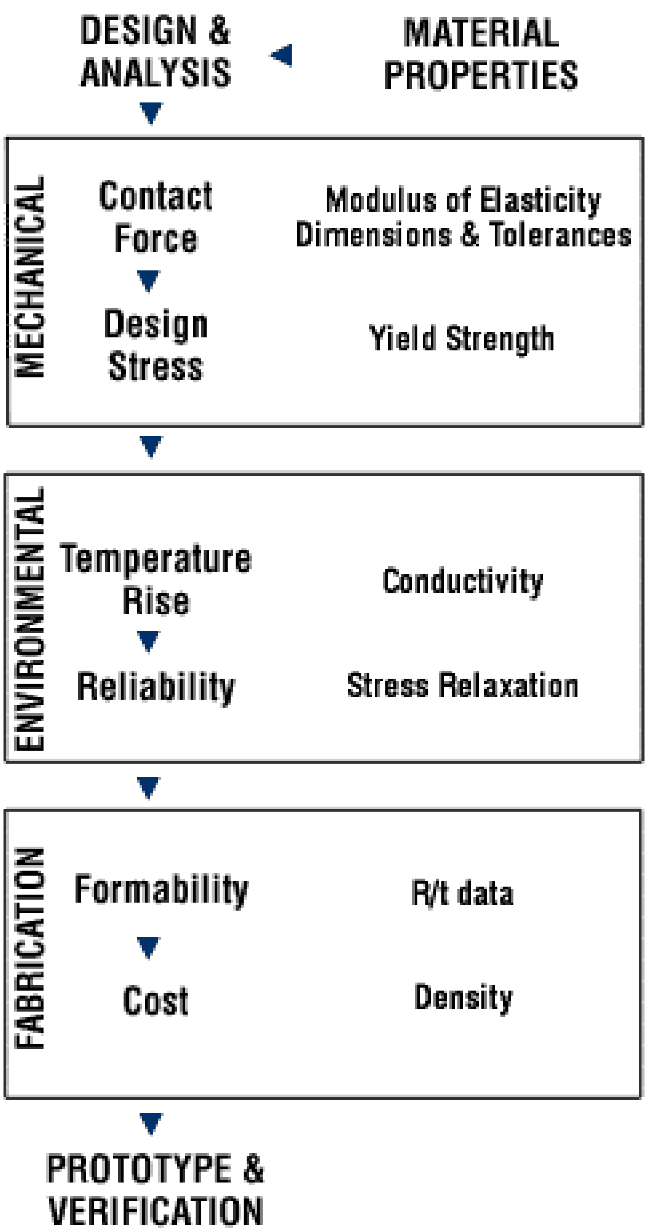
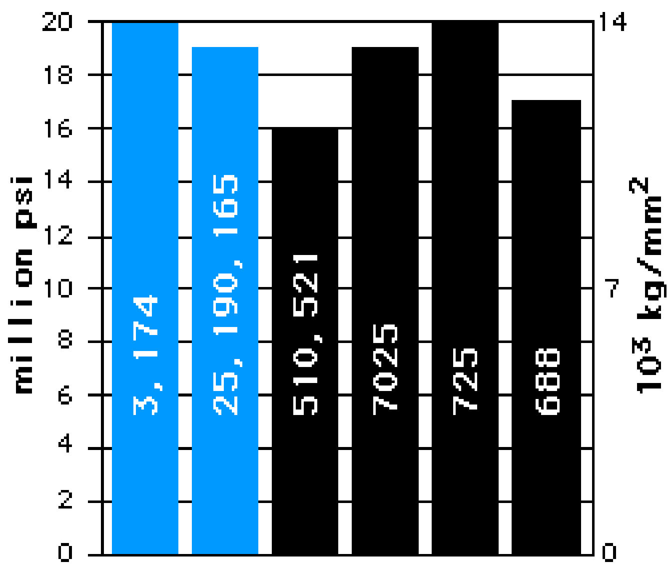


CHART 1:MODULUS OF ELASTICITY

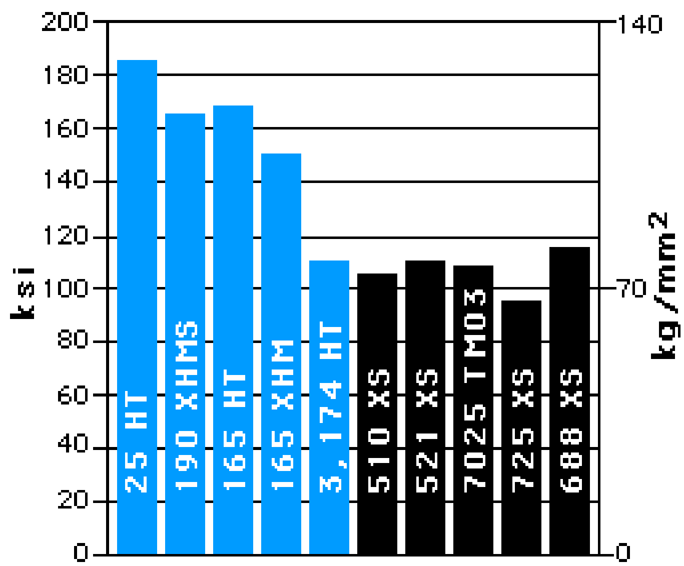


List of Charts

Chart 5b Chart 2

Design Guide
Chart 1

CHART 2: MAXIMUM YIELD STRENGTH

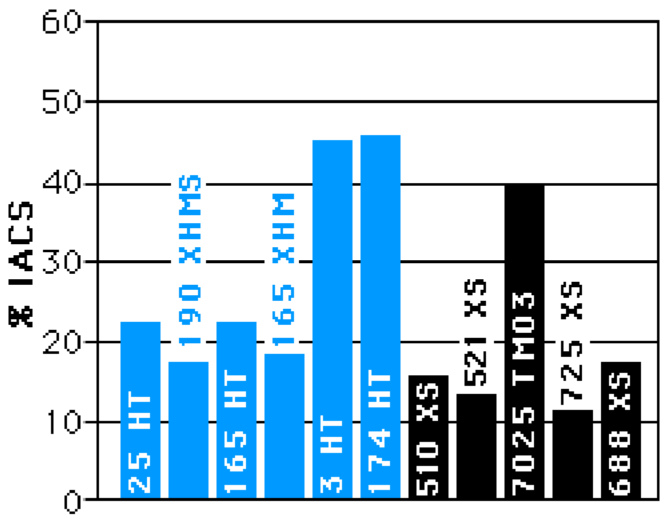


List of Charts

Chart 1 Chart 3

Design Guide
Chart 2

CHART 3: ELECTRICAL CONDUCTIVITY

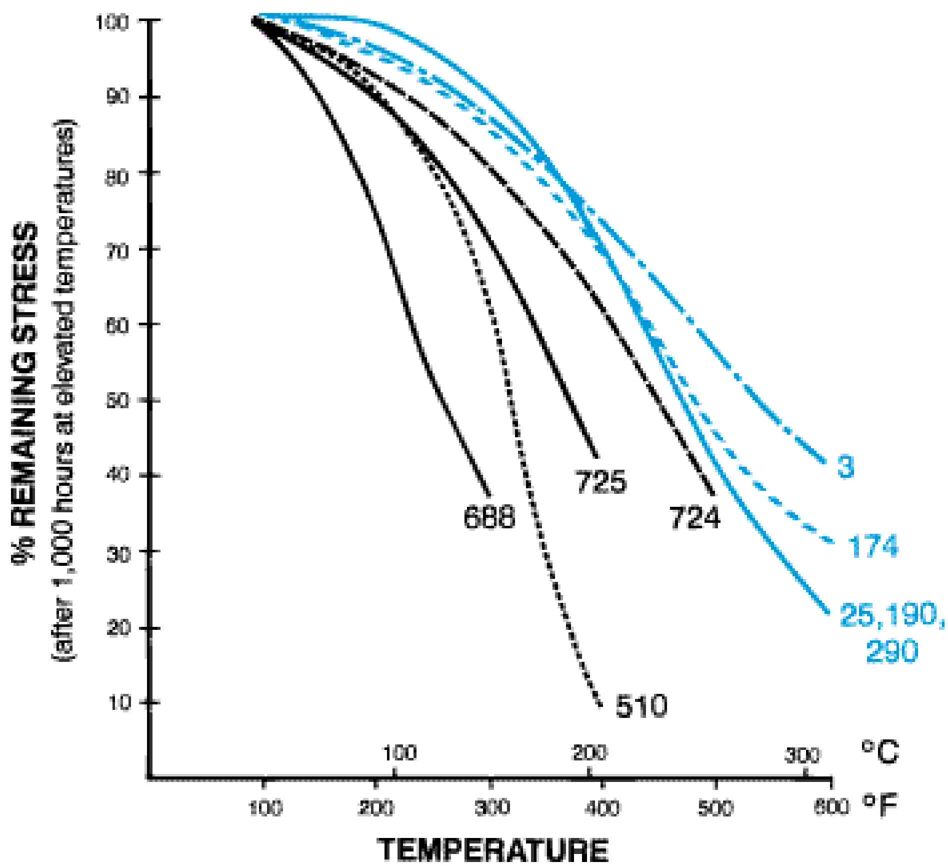


List of Charts

Chart 2 Chart 4

Design Guide
Chart 3

FIGURE 46: EFFECT OF TEMPERATURE ON STRESS RELAXATION



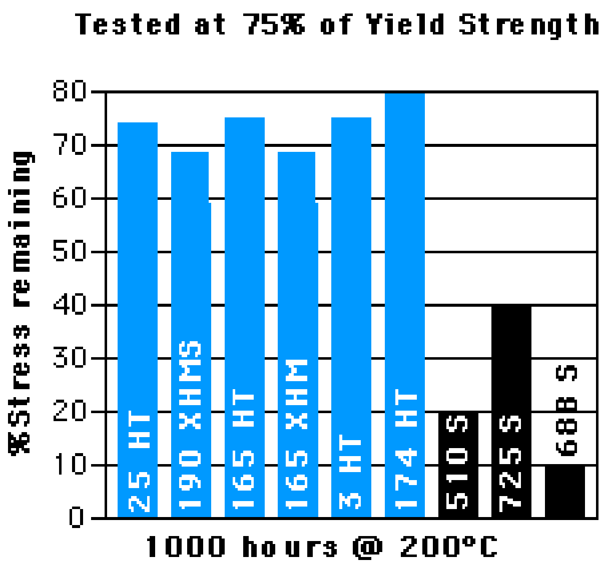
List of Figures

Figure 45

Figure 47

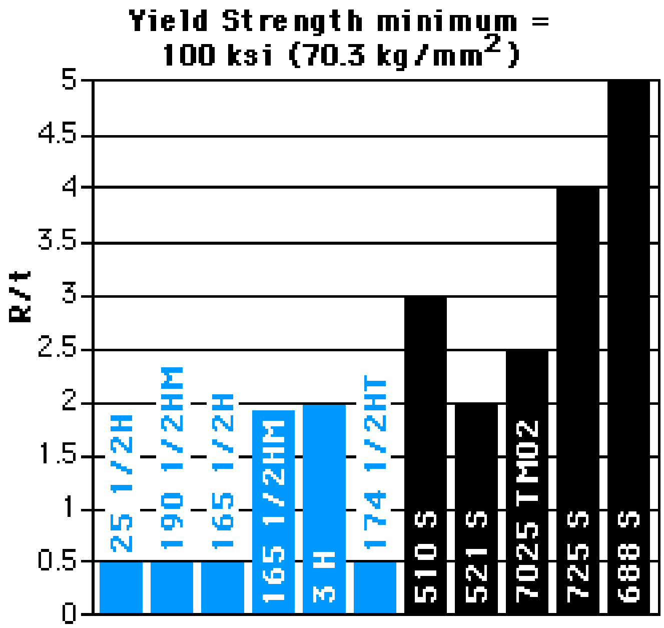
Design Guide
Figure 46

CHART 4: STRESS RELAXATION



List of Charts
Chart 3
Chart 5a
Design Guide
Chart 4

CHART 5a: LONGITUDINAL FORMABILITY

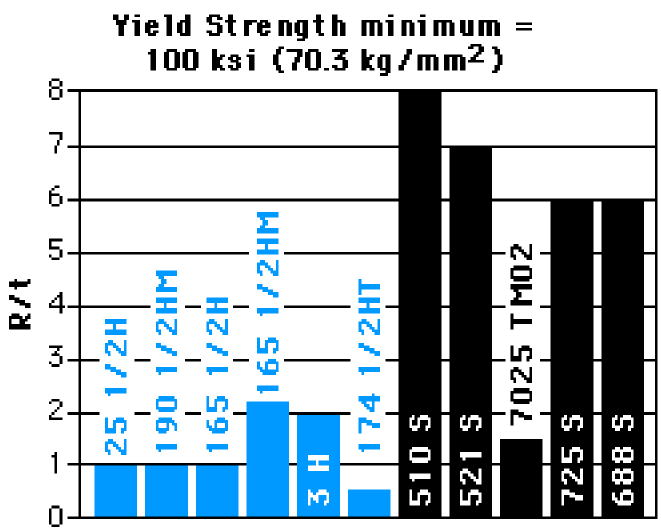


List of Charts

Chart 4   Chart 5b

Design Guide
Chart 5a

CHART 5b: TRANSVERSE FORMABILITY

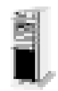
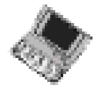


List of Charts

Chart 5a Chart 1

Design Guide
Chart 5b

Table 24 - Miniaturization

Product Evolution	**Then** 	**Now** 

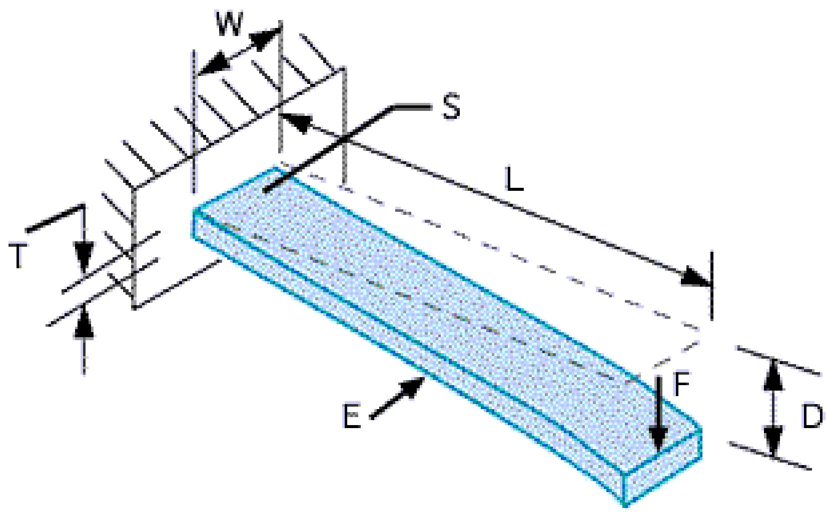
Grid	≥0.100" (2.54 mm)	≤0.050" (1.27 mm)
Post Size	0.025" (0.635 mm)	0.015" (0.381 mm)
Material Thickness	0.010 - 0.015" (0.259 - 0.381 mm)	0.003 - 0.010" (0.08 - 0.254 mm)
Contact Force	≥100 grams (1 N)	≤50 grams (0.5 N)

List of Tables

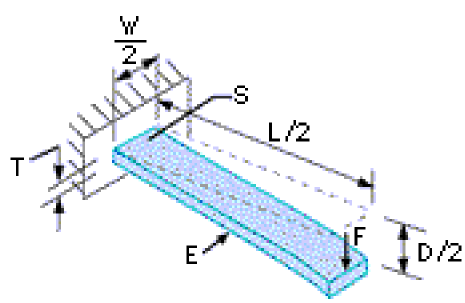
Table 23 Table 1

Design Guide - Table 24

FIGURE 47: MINIATURIZATION



Original design



Miniaturized design

List of Figures

Figure 46 Figure 1

Design Guide
Figure 47

APPENDIX

Beryllium Copper alloys and forms

High Strength alloys

C17200

- **Alloy 25** -- highest strength and hardness of any commercial Cu alloy -- age hardenable -- available in strip, rod, bar, plate, wire and tube forms.
- **Alloy 190** -- mill hardened strip product (similar to 25) -- available is strip form only.

  - cost effective by elimination of age hardening and cleaning after stamping

- **Alloy 290** -- similar to 190 with improved formability -- available in strip form only.

C17300

- **Alloy M25** -- free machining version of 25 -- Pb added to promote formation of finely divided chips -- available in rod form only

C17000

- **Alloy 165** -- less Be than 25 -- lower strength and cost -- available in rod, bar, wire, plate and tube forms.

High conductivity alloys

C17510

- **Alloy 3 --** moderate yield strength, 40-60% IACS -- both heat treatable and mill hardened tempers available in rod, bar, plate, wire and tube forms. Strip is mill hardened only

C17500

- **Alloy Brush 60** -- High conductivity, moderate strength, good stress relaxation resistance Mill hardened strip product with execellent formability.

C17410

- **Alloy 174 --** upgrade performance of phosphor bronze -- high conductivity and stress relaxation resistance -- mill hardened strip product

Nickel Beryllium

Brush Alloy **360** (UNS No. N03360) contains approximately 2% beryllium and like copper beryllium alloys, it is age hardenable. Nickel beryllium alloys are magnetic. The physical properties of Alloy 360 are:

- Density = 0.294 lb./in^3 (8.13 g/cm^3)
- CTE = 8.0 x 10^{-6}/°F (14.4 x 10^{-6}/C)
- Thermal conductivity = 28 BTU/(ft*hr*F) (48.0 W/m*K)
- Elastic modulus = 28.5 x 10^6 psi (20 x 10^3 kg/mm^2)
- Electrical conductivity = 4-6% IACS Alloy 360 is available in strip form.

Availability

Brush Wellman maintains a worldwide network of service centers, independent distributors and authorized agents. People in this network can answer your inquiry, process your order and assist with your special requirements. These resources maintain stocks of beryllium copper alloy products in a wide range of alloys, tempers and sizes to expedite your orders. They also provide precision slitting, sawing, tension leveling, traverse winding and other custom services to meet your exacting requirements.

Strip: Brush Wellman's strip products are available in gauges down to 0.002 inch (0.05 mm) with widths from 0.050 to 18 inches (1.27 to 457.2 mm). In instances where reduced gauges are necessary, Brush Wellman will provide assistance in locating suitable suppliers. While Brush Wellman's strip product is typically shipped in flat coil, it is also available on traverse wound reels up to 1000 pounds (454 Kg).

Wire: Brush Wellman's wire product is available in round, square and rectangular forms in gauges ranging from 0.050 to 0.250 inches (1.27 to 6.35 mm).

Rod: Brush Wellman's rod product is readily available in 12 feet (3.66 m) maximum straight lengths with gauges ranging from 0.050 to 0.500 inches (1.27 to 12.7 mm). Custom lengths are available on request.

Tube, Bar and Plate: Brush Wellman manufactures its beryllium copper products in tube, bar and plate forms. Questions regarding specific availability should be addressed to the company's Sales Engineering department.

Health and Safety

Handling copper beryllium in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on copper beryllium, contact Brush Wellman Inc. in Cleveland, Ohio at **216-486-4200**.

Standard Cantilever Beam Equation Transforms

Conversion Factors

To Convert From	To	Multiply By
angstrom	m	1.0×10^{-10}
angstrom	in	3.937×10^{-9}

Btu·ft/hr·ft^2°F	W/m·K	1.7296
°F	°C	$T_C = (T_F - 32) / 1.8$
g	lb	0.00221
g/cm^3	kg/m^3	1000
in	m	0.0254
in^2	m^2	6.4516 x 10^{-4}
in^3	m^3	1.6387 x 10^{-5}
kgf	N	9.80665
ksi	MPa	6.8948
ksi	kg/mm^2	0.7031
% IACS	ohm-in	6.79 x 10^{-7}
	ohm-cm	1.72 x 10^{-6}
lb	g	453.6
lbf	N	4.4482
uin	m	2.54 x 10^{8}
mil	m	2.54 x 10^{-5}

Further Reading

1) R. Holm, "Electric Contacts," 4th edition, Springe-Verlag, New York, 1967

2) W. Young, "Roark's Formulas for Stress & Strain," 6th edition, McGraw Hill, 1989

3) "Connectors and Interconnections Handbook", Volume 1-4, Electronic Connector Study Group, Fort Washington, PA, 1982

4) D. Seraphin, R. Lasky, C.Y. Li, "Principles of Electronic Packaging," McGraw Hill, 1989

5) L. Durney, "Electroplating Engineering Handbook," 4th edition, Von Nostrand Reinhold, 1984

6) J. Crane, R. Mroczkowski, D. Jeannotte, "Materials Issues for Advanced Electronic and Opto-Electronic Connectors", Minerals, Metals & Materials Society, 1991

7) H. W. Hayden, W. G. Moffatt, J. Wulff, "The Structure and Properties of Materials Volume III - Mechanical Behavior," Wiley, 1965

8) G. Dieter, "Mechanical Metallurgy," 2nd edition, McGraw Hill, 1976

9) C. Harper, R. Sampson, "Electronic Materials & Processes Handbook," 2nd edition, McGraw Hill, 1994

10) MacNeal, "Finite Elements: Their Design and Performance"

TABLE 14a - STRIP DIMENSIONAL TOLERANCES

Strip Thickness (inches)	BRUSH STD Tolerance (+/- inches)	ASTM B 248 Special Tolerance (+/- inches)	ASTM B 248 STD Tolerance (+/- inches)
over - including			
0.0020 - 0.0040	0.00015	0.0002	0.0004
0.0040 - 0.0060	0.00020	0.0003	0.0006
0.0060 - 0.0090	0.00025	0.0004	0.0008
0.0090 - 0.0130	0.00030	0.0005	0.0010
0.0130 - 0.0170	0.00040	0.0007	0.0013
0.0170 - 0.0210	0.00040	0.0008	0.0015
0.0210 - 0.0260	0.00040	0.0010	0.0020
0.0260 - 0.0370	0.00060	0.0013	0.0025
0.0370 - 0.0500	0.00080	0.0015	0.0030
0.0500 - 0.0730	0.00100		0.0035

TABLE 14b - STRIP DIMENSIONAL TOLERANCES (METRIC)

Strip Thickness (mm)	BRUSH STD Tolerance (+/- mm)
0.05 - 0.10	0.0038
0.10 - 0.20	0.006
0.20 - 0.30	0.008
0.30 - 0.70	0.010
0.70 - 1.0	0.016
1.0 - 1.3	0.020
1.3 - 2.0	0.025

Wire

(See Tables 15a & b)

Table 13 - Electrical and Thermal Conductivity

Alloy	Temper	Electrical (% IACS min.)	Thermal (BTU/ft-hr-°F)	Thermal (W/m-k)	Conductivity Product (% IACS X BTU/ft-hr-oF)
25	AT 1/4 HT 1/2 HT HT	22	60	105	1320
190, 290	All Tempers	17	60	105	1020
60	3/4 HT HT	50	128	219	6400
199	1/4 H 1/2 H H EH EHP SHP ESHP XSHP	13	31	54	403
3	AT HT	45 48	140	240	6300
174	1/2 HT HT	50 48	135	230	6750 6480
260	H	28	70	120	
194	S	60	150	260	
510	1/2 H H S	15 15 15	40	70	600
521	1/2 H H S	13 13 13	36 36 36	62	468
654	1/2 H, H X, XS	7	21	36	147
688	1/2 H, H S XS	17	40	69	680
725	1/2 H, H S	11	31	54	341 310
7025	TM02 TM03	40 35	98		3920 3430

Table 4 - Temper Designation

Brush Designation	ASTM Designation	Description	Cold Rolled or Drawn Thickness Reduction (%) STRIP	WIRE
A	TB00	Solution Annealed	0	0
1/4 H	TD01	Quarter Hard (work hardened)	11	21
1/2 H	TD02	Half Hard	21	37
3/4 H	TD03	Three-Quarter Hard	29	50
H	TD04	Hard	37	60
S	TD06	Spring	60	84
XS	TD08	Extra Spring	69	90
AT	TF00	Heat treated - age or precipitation hardened		
1/4 HT	TH01	(Standard heat treatment following work hardening & forming)		
1/2 HT	TH02			
3/4 HT	TH03			
HT	TH04			
AM	TM00	Mill hardened - no additional treatment needed		
1/4 HM	TM01			
1/2 HM	TM02			
3/4 HM	TM03			
HM	TM04			
SHM	TM05			
XHM	TM06			
XHMS	TM08			

FIGURE 8: UNIAXIAL TENSILE TEST

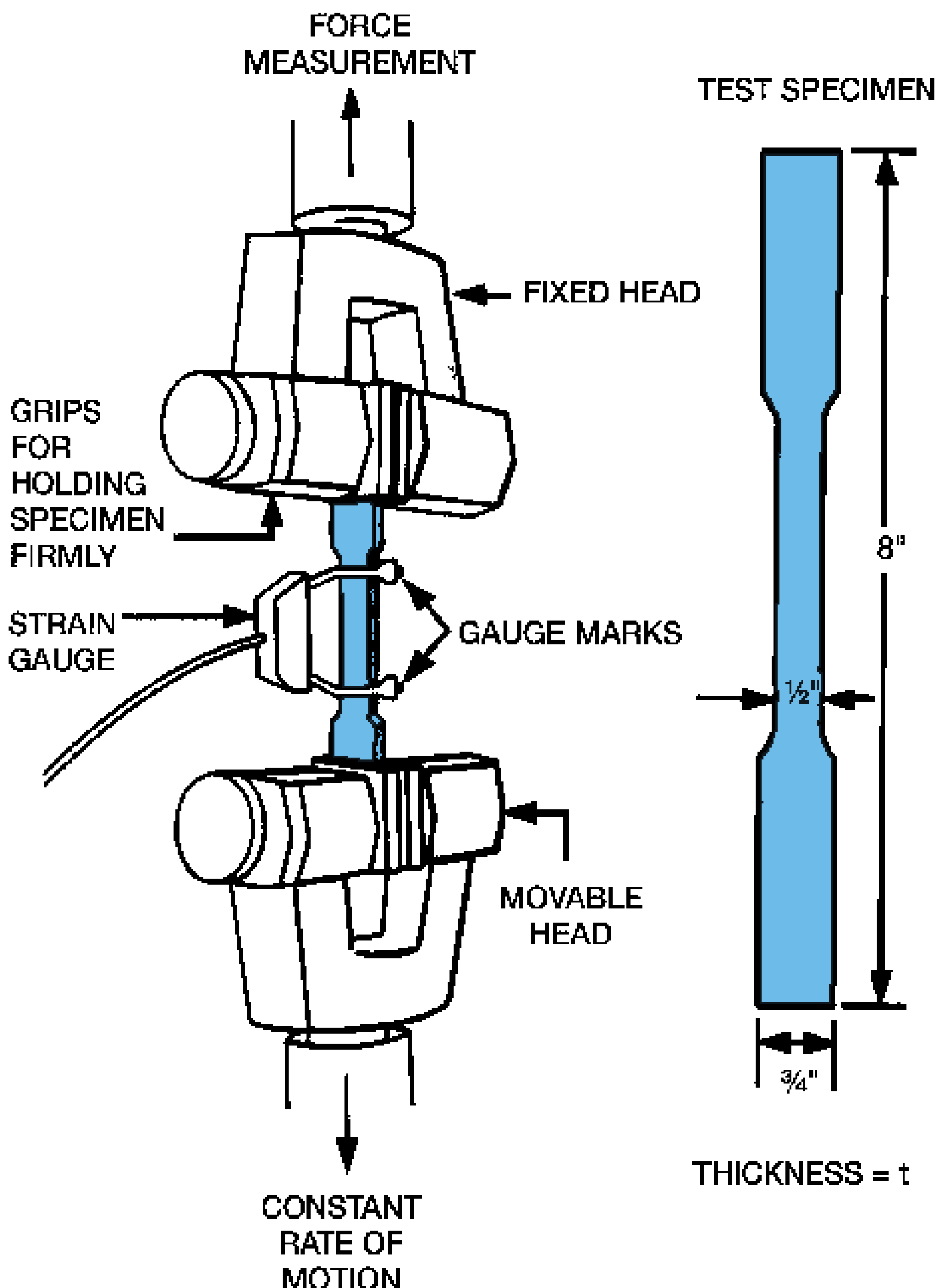


FIGURE 9: SIMPLE TENSION LOAD

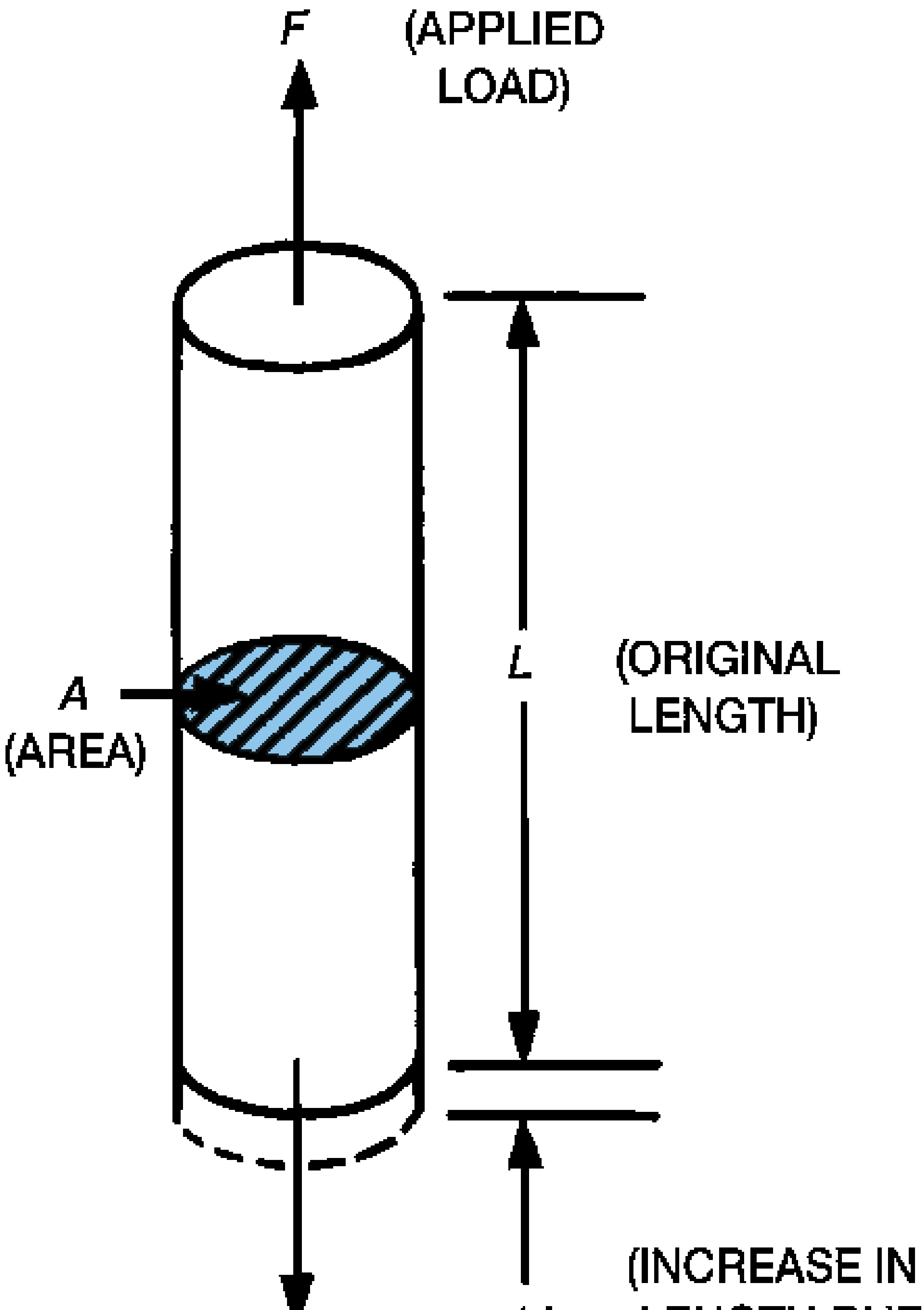


FIGURE 10: STRESS-STRAIN CURVE

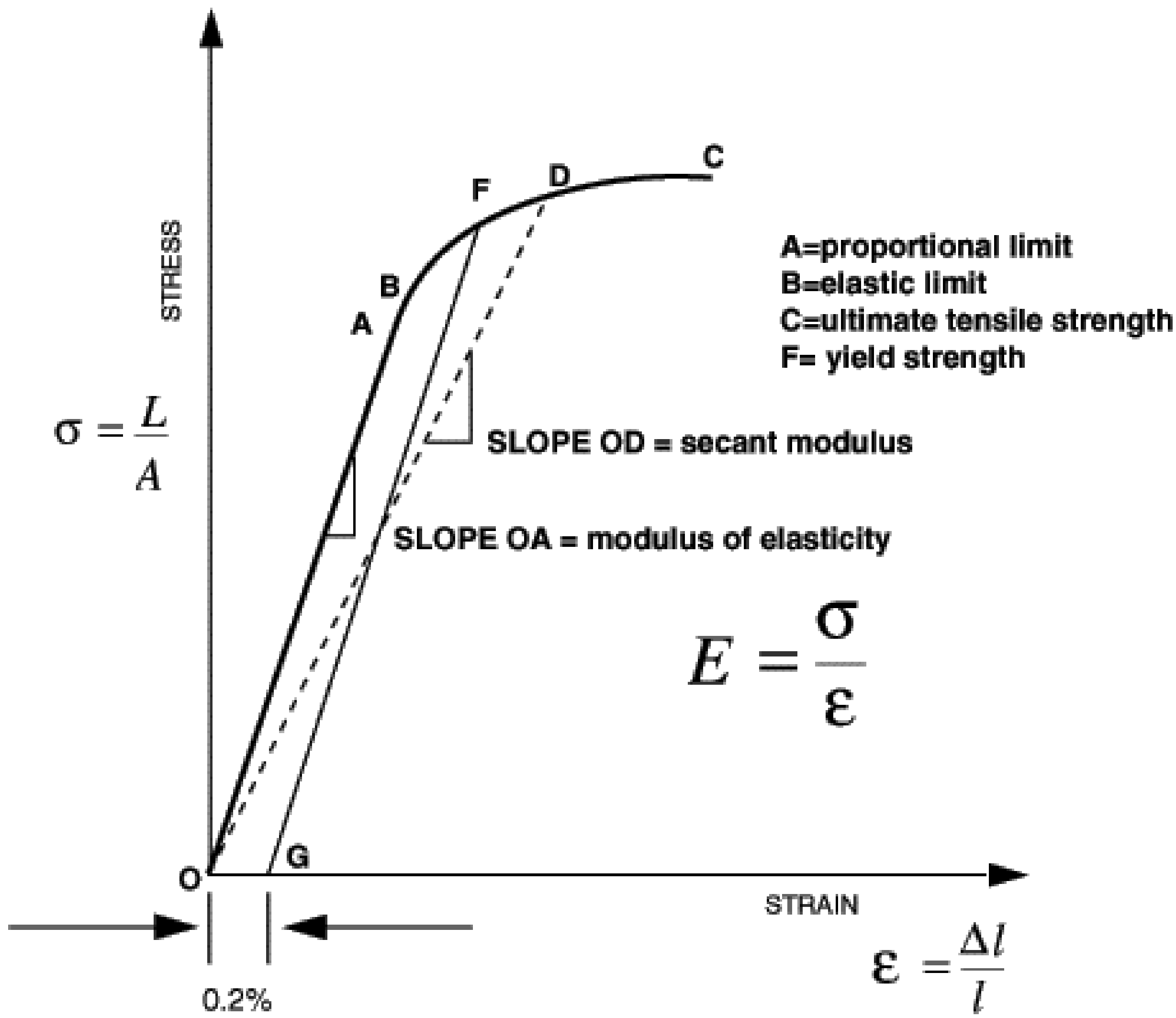


Figure 9 Figure 11

FIGURE 12: BEAM IN BENDING

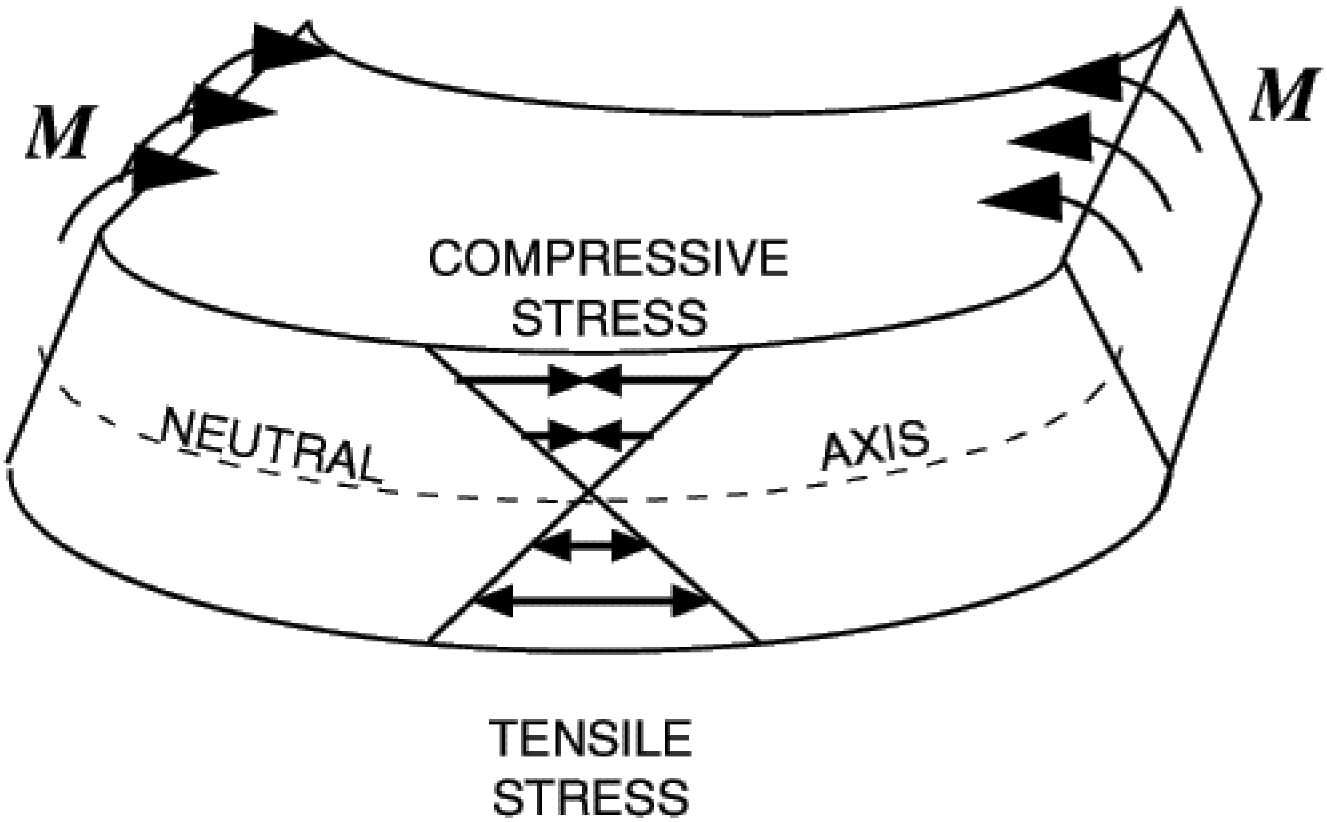


Figure 13 Figure 11

FIGURE 13: MAXIMUM SURFACE STRESS

deflection

Modulus of Elasticity

Maximum Surface Stress $$\sigma_{max} = \frac{3dEt}{2l^2}$$

beam thickness

beam length

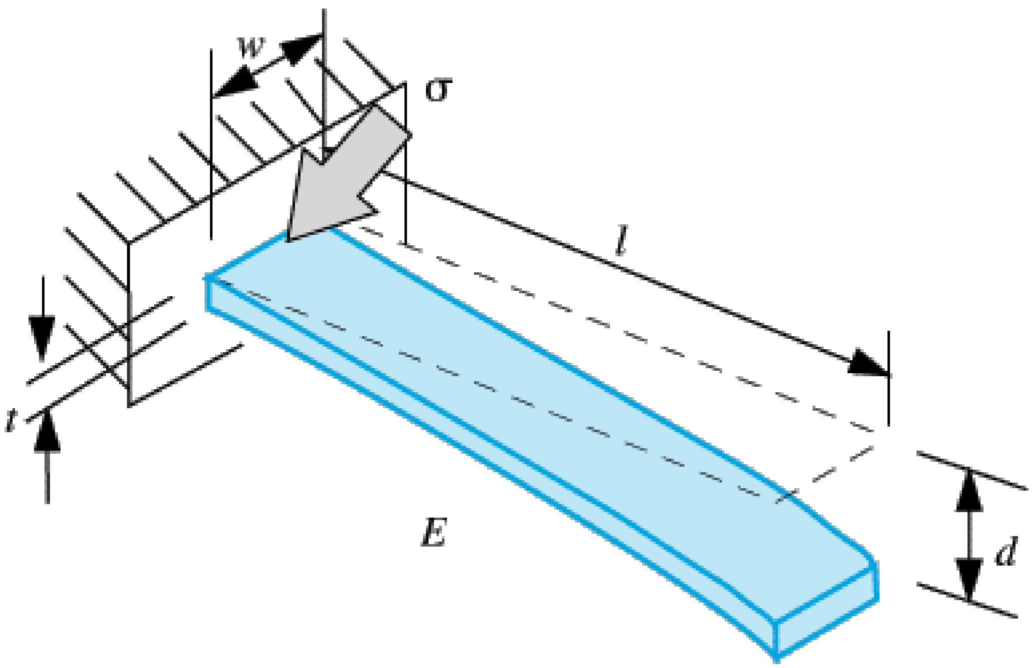


Figure 12 Figure 14

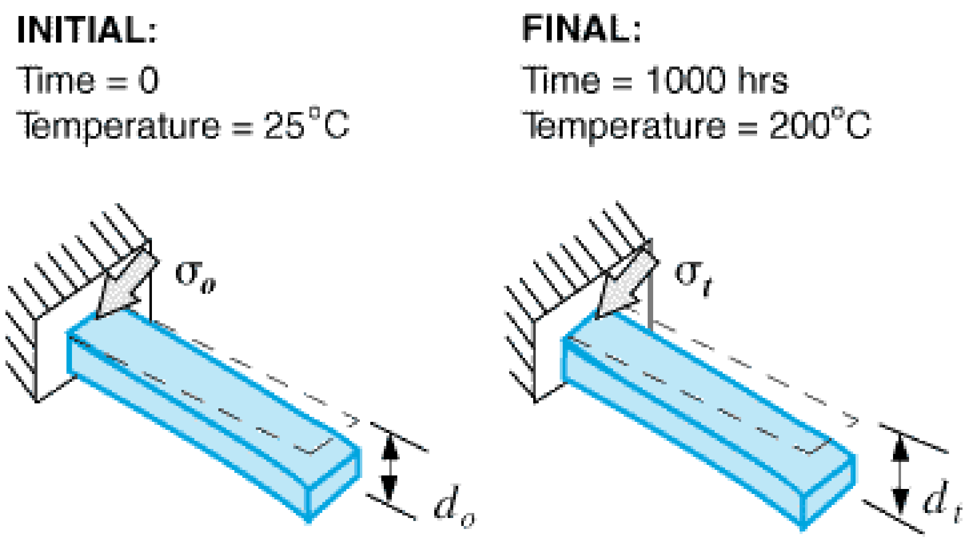
Table 5 - Strip Mechanical Properties

Alloy	Temper	Heat Treatment	Modulus of Elasticity (10^6 psi)	Modulus of Elasticity (10^3 kg/mm^2)	Yield Strength 0.2% Offset (ksi)	Yield Strength 0.2% Offset (kg/mm^2)	Tensile Strength (ksi)	Tensile Strength (kg/mm^2)	Total Elongation (%) min.
25	A	-	19	13.5	30-55	21-39	60-78	42-55	35
	1/4 H	-			60-80	42-57	75-88	52-62	20
	1/2 H	-			75-95	52-67	85-100	59-71	12
	H	-			90-115	63-81	100-120	70-85	2
	AT	3 hr at 600F			140-175	98-124	165-195	116-138	3
	1/4 HT	2 hr at 600F			150-185	105-130	175-205	123-145	3
	1/2 HT	2 hr at 600F			160-195	112-138	185-215	130-152	1
	HT	2 hr at 600F			165-205	116-145	190-220	133-155	1
190	AM	Mill	19	13.5	70-95	49-67	100-110	70-78	16
	1/4 HM	Hardened			80-110	56-78	110-120	77-85	15
	1/2 HM				95-125	66-88	120-135	84-95	12
	HM				110-135	77-95	135-150	94-106	9
	SHM				125-140	87-99	150-160	105-113	9
	XHM				135-170	94-120	155-175	108-124	4
	XHMS				150-180	105-127	175-190	123-134	3
290	TM00	Mill	19	13.5	75-95	52-67	100 min	70 min	19
	TM02	Hardened			95-115	66-81	120 min	84 min	14
	TM04				115-135	80-95	140 min	98 min	9
	TM06				135-155	94-109	155 min	109 min	6
	TM08				155-175	108-124	175 min	123 min	3
60	3/4 HT	Mill	20	14	95-115	66-81	115-135	81-105	11
	HT	Hardened	20	14	105-125	74-88	120-140	84 - 98	10
199	1/4 H	Mill	18	13	85-114	60-80	107-135	75-95	15
	1/2 H	Hardened	18	13	99-128	70-90	114-142	80-100	15
	H		18	13	121-135	85-95	121-149	85-105	8
	EH		18	13	121-149	85-105	128-157	90-110	5
	EHP		18	13	119-133	84-94	128-157	90-110	15
	SHP		18	13	123-138	86-97	132-161	93-113	10
	ESHP		18	13	136-151	96-106	145-171	102-120	5
	XSHP		18	13	152-174	107-122	165-189	116-133	-
174	1/2 HT	Mill Hard	20	14	80-100	56-70	95-115	67-80	10
	HT				100-120	70-84	110-130	77-91	7
260	H	Not Age Hardenable	16	11.3	60-75	42-53	71-81	50-57	6
194	S	Not Age Hardenable	17.5	12.3	67-74	47-52	70-76	49-53	1
510	1/2 H	Not Age	16	11	47-68	33-48	58-73	41-51	16
	H	Hardenable			74-88	52-62	76-91	53-64	10
	S				92-108	65-76	95-110	67-77	4
521	1/2 H	Not Age	16	11	51-75	36-53	69-84	49-59	25
	H	Hardenable			78-95	55-67	85-100	60-70	12
	S				100-113	70-79	105-119	74-84	3
654	1/2 H	Not Age	17	12	66-92	46-65	86-101	60-71	11
	H	Hardenable			94-109	108-120	108-120	76-84	4
	S				112-123	80-86	124-133	87-94	2
	XS				118-131	83-92	131-140	92-98	1
688	1/2 H	Not Age	17	12	82-102	58-72	97-112	68-79	9
	H	Hardenable			95-108	67-76	106-120	75-84	4
	S				111-117	78-82	123-133	86-94	1
	XS				117 min	78 min	130 min	91 min	2 max
7025	TM02	Mill Hard	19	13.5	85-110	60-77	95-120	67-84	7
	TM03				95-120	67-84	100-125	70-88	5
725	1/2 H	Not Age	20	14	59-78	41-55	65-80	46-56	6
	H	Hardenable			73-88	51-62	75-90	53-63	3
	S				83-97	58-68	85-100	60-70	1

TABLE 6 - Hardness Values

Alloy	Temper	Hardenss: Diamond Pyramid DPH	Hardenss: Rockwell B or C	Hardenss: Rockwell Superficial
25	A	90-144	B45-78	30T46-67
	1/4 H	121-185	B68-90	30T62-75
	1/2 H	176-216	B88-96	30T74-79
	H	216-287	B96-102	30T79-83
	AT	353-413	C36-42	30N56-62
	1/4 HT	353-424	C36-43	30N56-63
	1/2 HT	373-435	C38-44	30N58-63
	HT	373-446	C38-45	30N58-65
190	AM	210-251	B95-C23	30N37-44
	1/4 HM	230-271	C20-26	30N41-47
	1/2 HM	250-301	C23-30	30N44-51
	HM	285-343	C28-35	30N48-55
	SHM	309-363	C31-37	30N52-56
	XHM	317-378	C32-38	30N52-58
	XHMS	325-413	C33-42	30N53-62
290	TM00	225-309	B98-C31	30T81-30N52
	TM02	255-339	C25-34	30N46-54
	TM04	285-369	C28-38	30N48-58
	TM06	317-393	C32-40	30N52-60
	TM08	345-429	C35-43	30N55-62
3	A	65-125	B20-45	30T28-45
	H	144-176	B78-88	30T69-75
	AT	195-275	B92-100	30T77-82
	HT	216-287	B95-102	30T79-83
174	1/2 HT	180-230	B89-98	30T75.5-81.9
	HT	210-278	B95-C27	30T79-30N48

FIGURE 14: STRESS RELAXATION CONDITIONS



$$d_0 = d_t$$

$$\sigma_0 \neq \sigma_t$$

FIGURE 15: STRESS RELAXATION VS. NORMAL FORCE

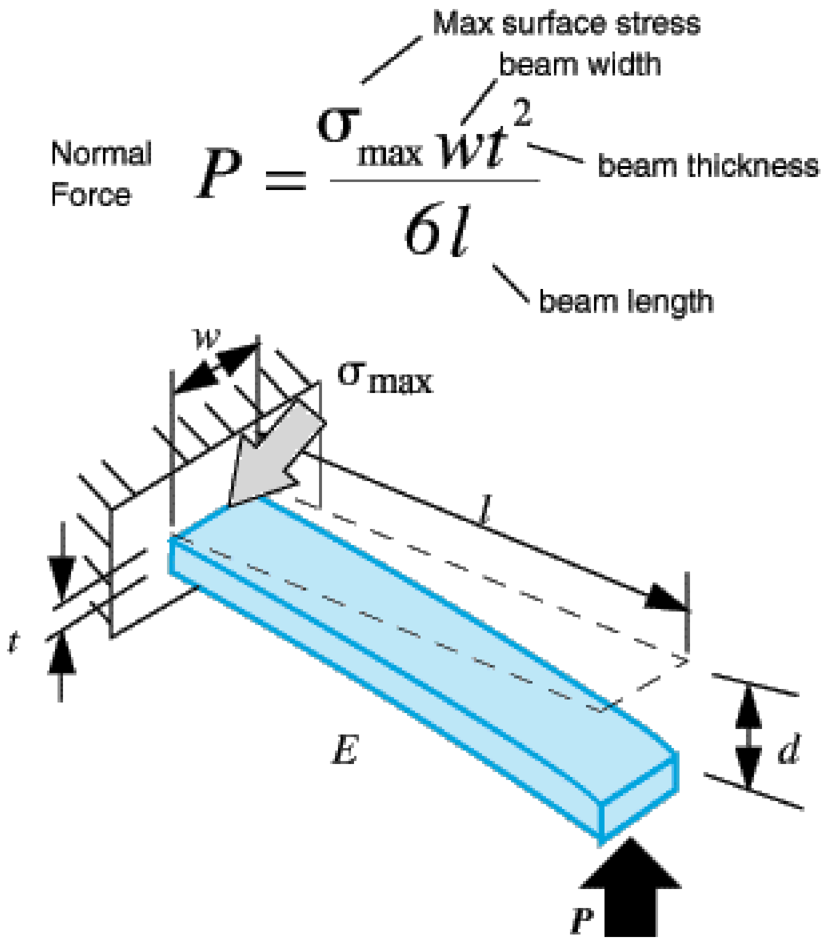


FIGURE 16: STRESS RELAXATION TEST APPARATUS

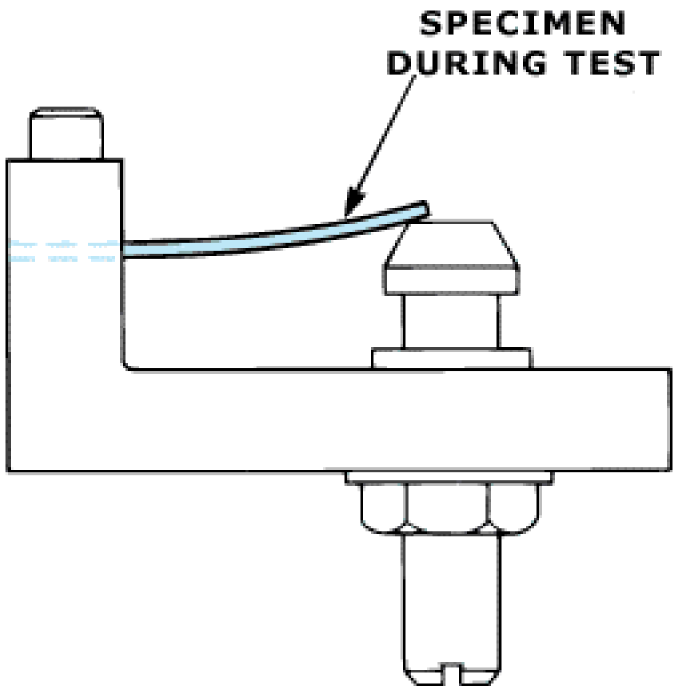


Figure 15 Figure 17

FIGURE 17: STRESS RELAXATION CURVES

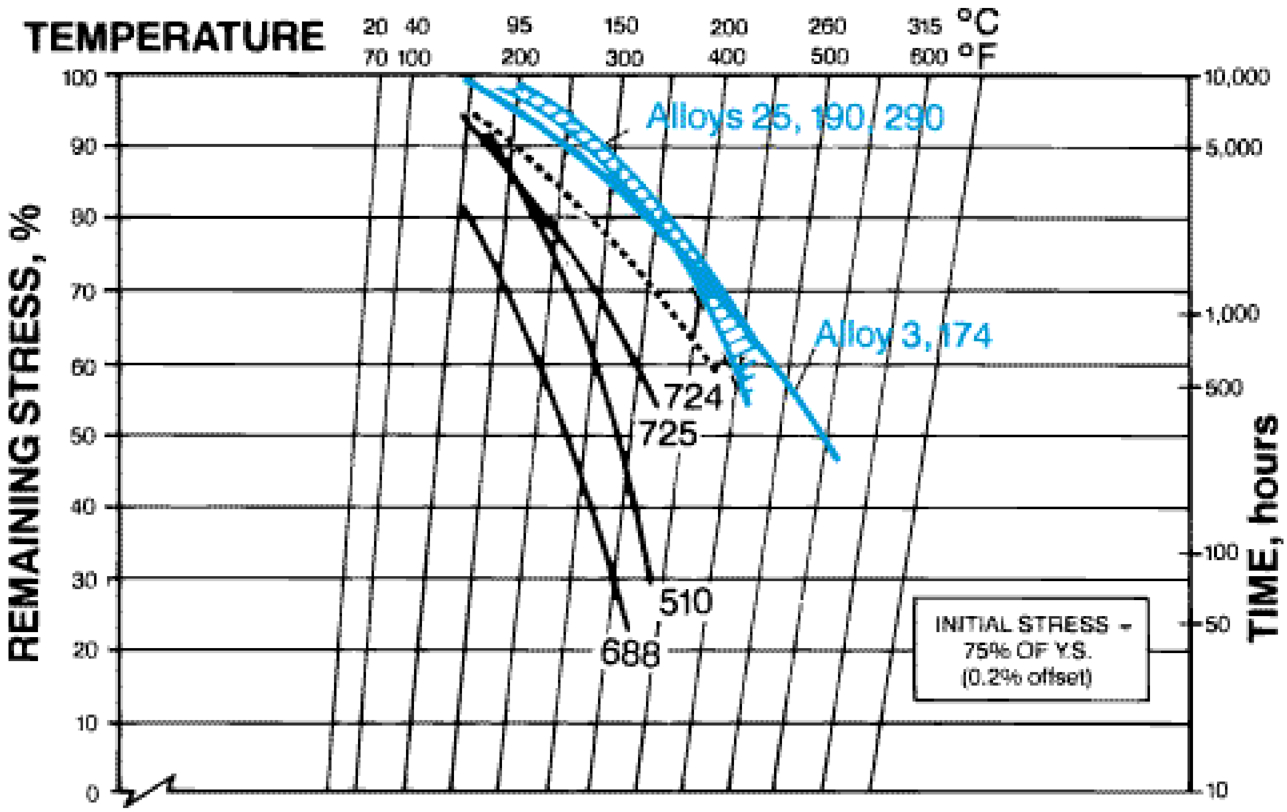


Figure 16 Figure 18

Table 7 - Stress Relaxation

Alloy	Temper	Remaining Stress % (75% of 0.2% Offset Yield Strength) 1000 hours at 100°C (212°F)	Remaining Stress % (75% of 0.2% Offset Yield Strength) 1000 hours at 200°C (392°F)
25	AT	96	70
	1/4 H	96	70
	1/2 HT	97	73
	HT	98	74
190	AM	97	67
	1/4 HM	97	67
	1/2 HM	97	67
	HM	98	68
	SHM	98	68
	XHM	98	69
	XHMS	98	69
290	TM00	97	76
	TM02	97	76
	TM04	98	77
	TM06	99	78
	TM08	99	78
60	3/4 HT	95	64
	HT	97	75
3	AT	94	72
	HT	96	75
	HTR	96	75
	HTC	94	72
174	1/2 HT	94	70
	HT	95	76
260	H	41	8
194	S	-	-
510	1/2 H	85	-
	H	83	-
	S	77	20
521	1/2 H	88	-
	H	83	-
	S	75	-
654	S	72	-
688	S	72	10
725	S	89	40

Table 8 - Stress Relaxation Equation Coeeficients

Alloy & Temper	Test Temperature °F	Test Temperature (°C)	Equation Coefficients A	Equation Coefficients B
25 1/4 HT	257	125	97.83	0.0789
	302	150	96.61	0.1390
	392	200	98.22	0.7492
25 1/2 HT	257	125	98.33	0.0908
	302	150	97.67	0.2017
	392	200	94.36	0.7562
190 1/2 HM	257	125	99.03	0.2789
	302	150	97.04	0.6298
	392	200	62.48	0.8414
190 XHM	257	125	97.62	0.1039
	302	150	97.47	0.2417
	392	200	93.51	0.8184
290 TM04	257	125	100.86	0.1590
	302	150	97.77	0.2333
	392	200	97.10	1.3106
174 1/2 HT	257	125	94.49	0.1855
	302	150	91.17	0.2394
	392	200	79.18	0.2597
174 HT	257	125	97.84	0.1448
	302	150	94.78	0.1934
	392	200	89.68	0.2730
197 XH	257	125	90.36	0.2647
	302	150	83.77	0.3601
	392	200	62.93	0.5111
510 S	257	125	99.42	0.4227
	302	150	94.02	0.8491
	392	200	53.73	0.7616

FIGURE 18: FATIGUE TEST CONDITIONS

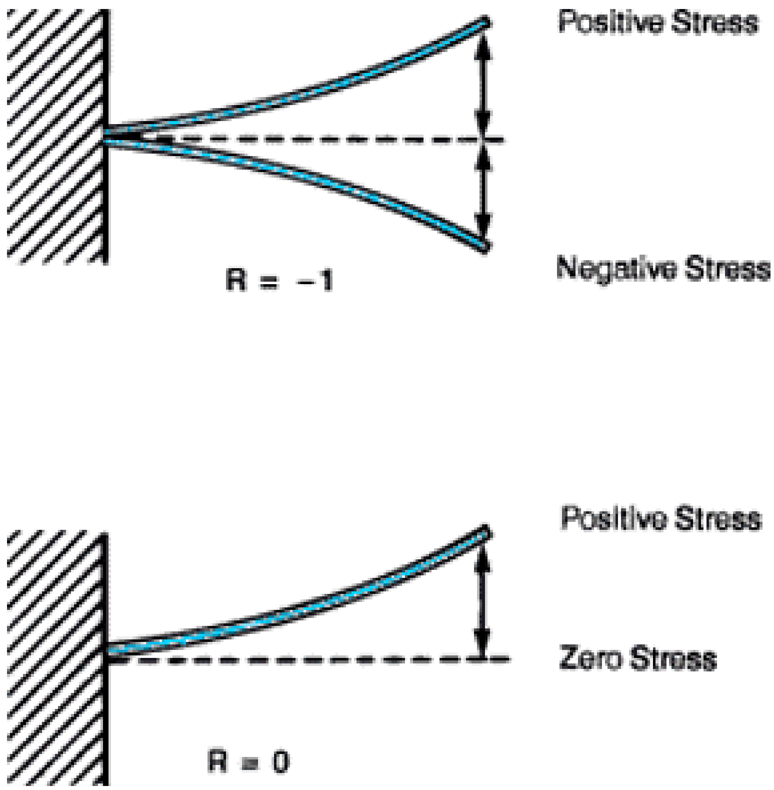


Figure 17 Figure 19

FIGURE 19:FATIGUE CURVES

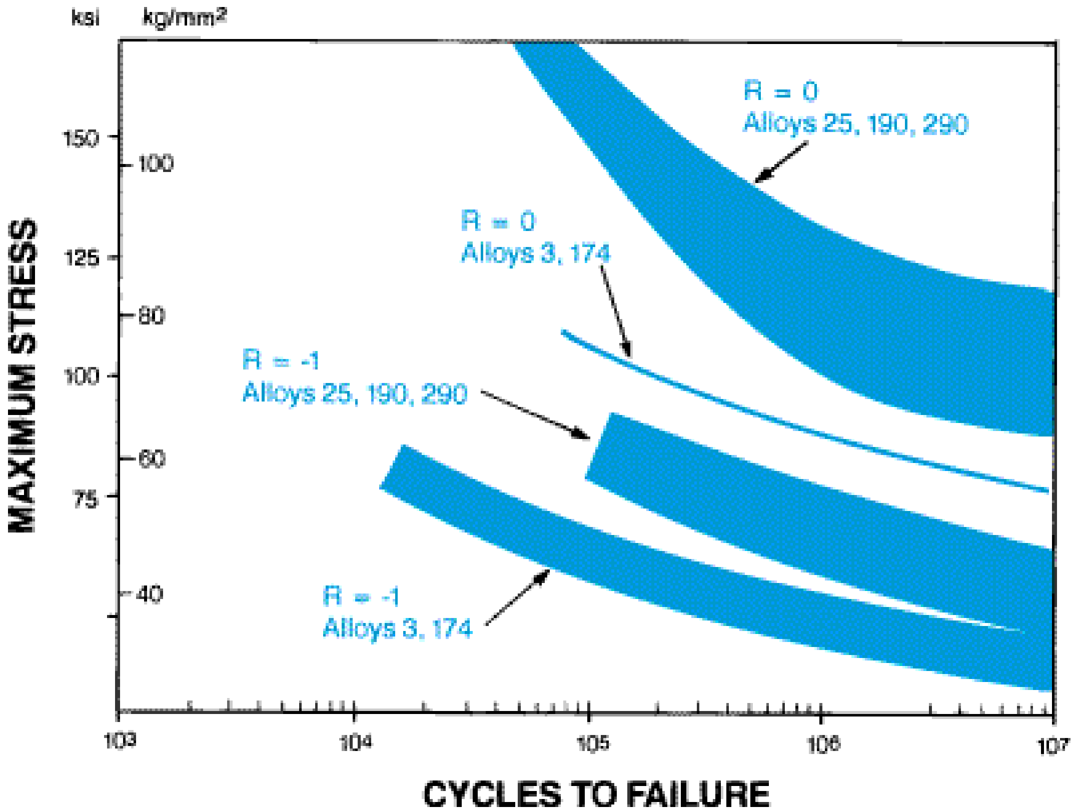


Figure 18 Figure 20

TABLE 6 - Hardness Values

Alloy	Temper	Hardenss		
		Diamond Pyramid DPH	Rockwell B or C	Rockwell Superficial
25	A	90-144	B45-78	30T46-67
	1/4 H	121-185	B68-90	30T62-75
	1/2 H	176-216	B88-96	30T74-79
	H	216-287	B96-102	30T79-83
	AT	353-413	C36-42	30N56-62
	1/4 HT	353-424	C36-43	30N56-63
	1/2 HT	373-435	C38-44	30N58-63
	HT	373-446	C38-45	30N58-65
190	AM	210-251	B95-C23	30N37-44
	1/4 HM	230-271	C20-26	30N41-47
	1/2 HM	250-301	C23-30	30N44-51
	HM	285-343	C28-35	30N48-55
	SHM	309-363	C31-37	30N52-56
	XHM	317-378	C32-38	30N52-58
	XHMS	325-413	C33-42	30N53-62
290	TM00	225-309	B98-C31	30T81-30N52
	TM02	255-339	C25-34	30N46-54
	TM04	285-369	C28-38	30N48-58
	TM06	317-393	C32-40	30N52-60
	TM08	345-429	C35-43	30N55-62
3	A	65-125	B20-45	30T28-45
	H	144-176	B78-88	30T69-75
	AT	195-275	B92-100	30T77-82
	HT	216-287	B95-102	30T79-83
174	1/2 HT	180-230	B89-98	30T75.5-81.9
	HT	210-278	B95-C27	30T79-30N48

FIGURE 20: CANTILEVER BEAM NORMAL FORCE

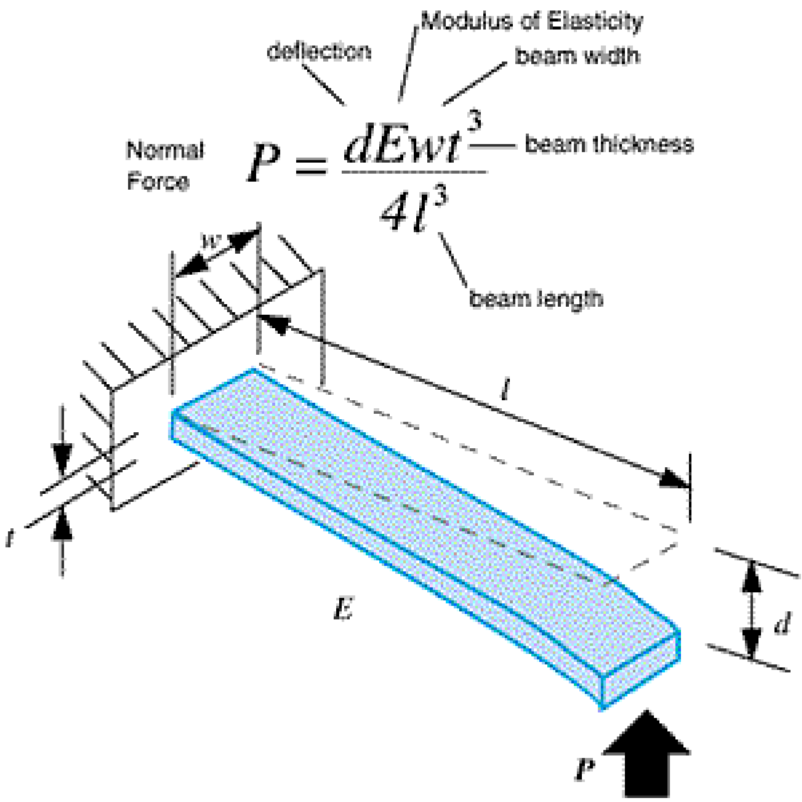


Figure 19 Figure 21a

FIGURE 21a:FRICTION FORCES

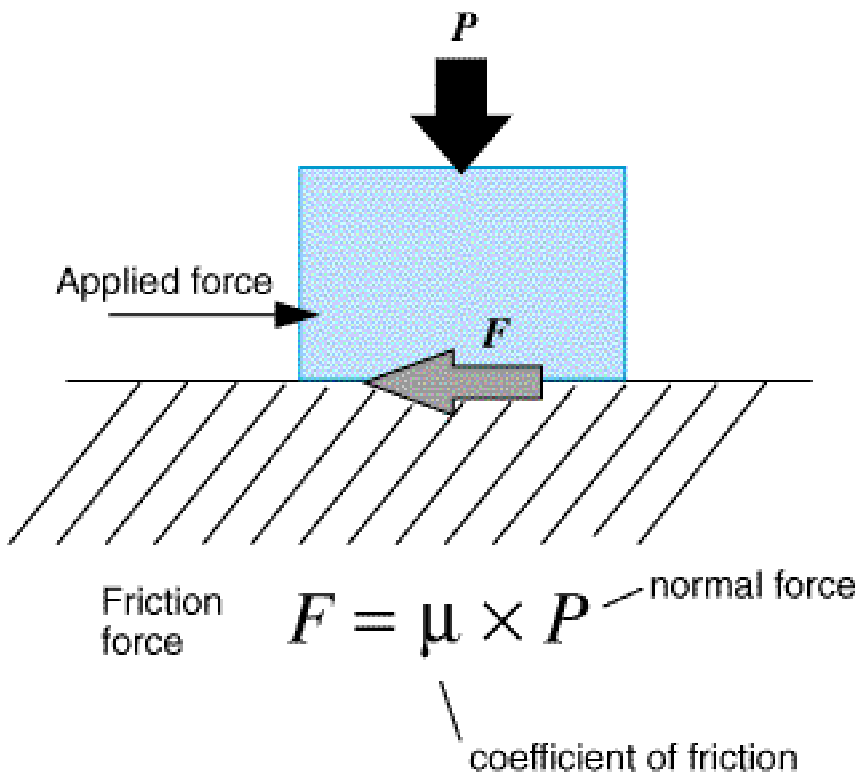
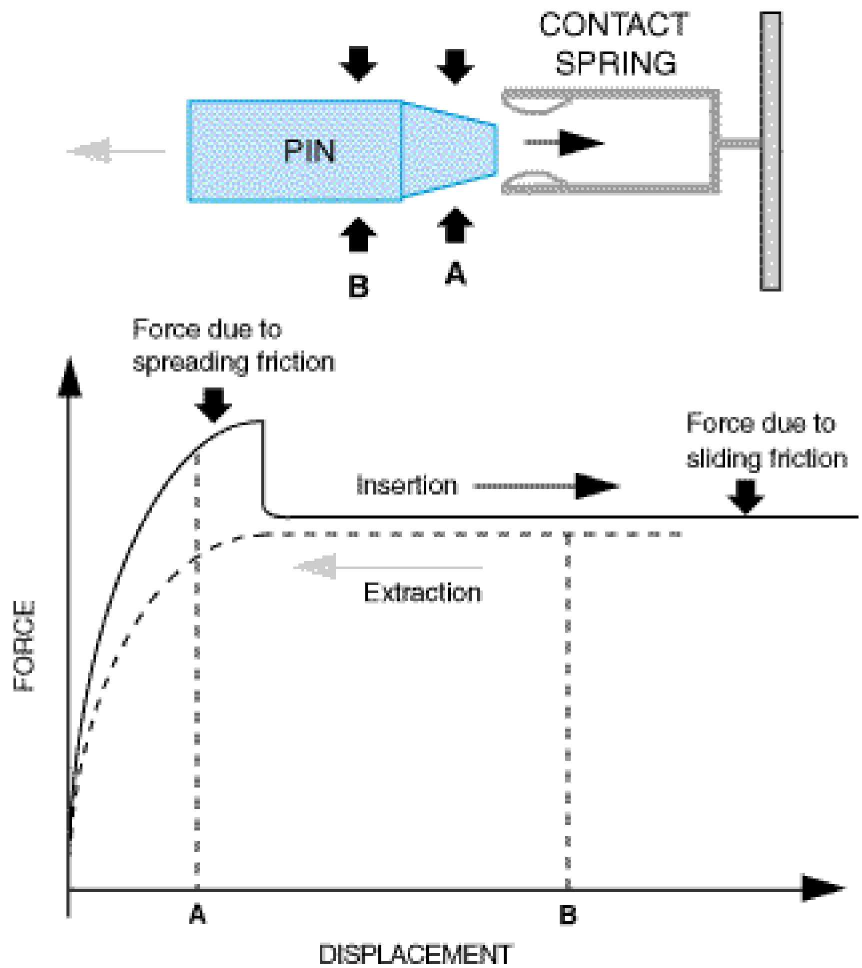


Figure 20 Figure 21b

FIGURE 21b: INSERTION AND EXTRACTION FORCES



Typical profile of sliding connector insertion and extraction forces

Figure 21a Figure 22

Table 10 - Normal Force Interrelationships

Affected by Normal Force	Affects Normal Force
Friction Force (Insertion / Withdrawal)	Contact Spring Rate
Wear Characteristics	Contact Pre-Load
Contact Spring Stresses	Contact Beam Deflection
Contact Housing Stresses	Permanent Set
Contact Resistance	Stress Relaxation

FIGURE 22:STRAIN HARDENING

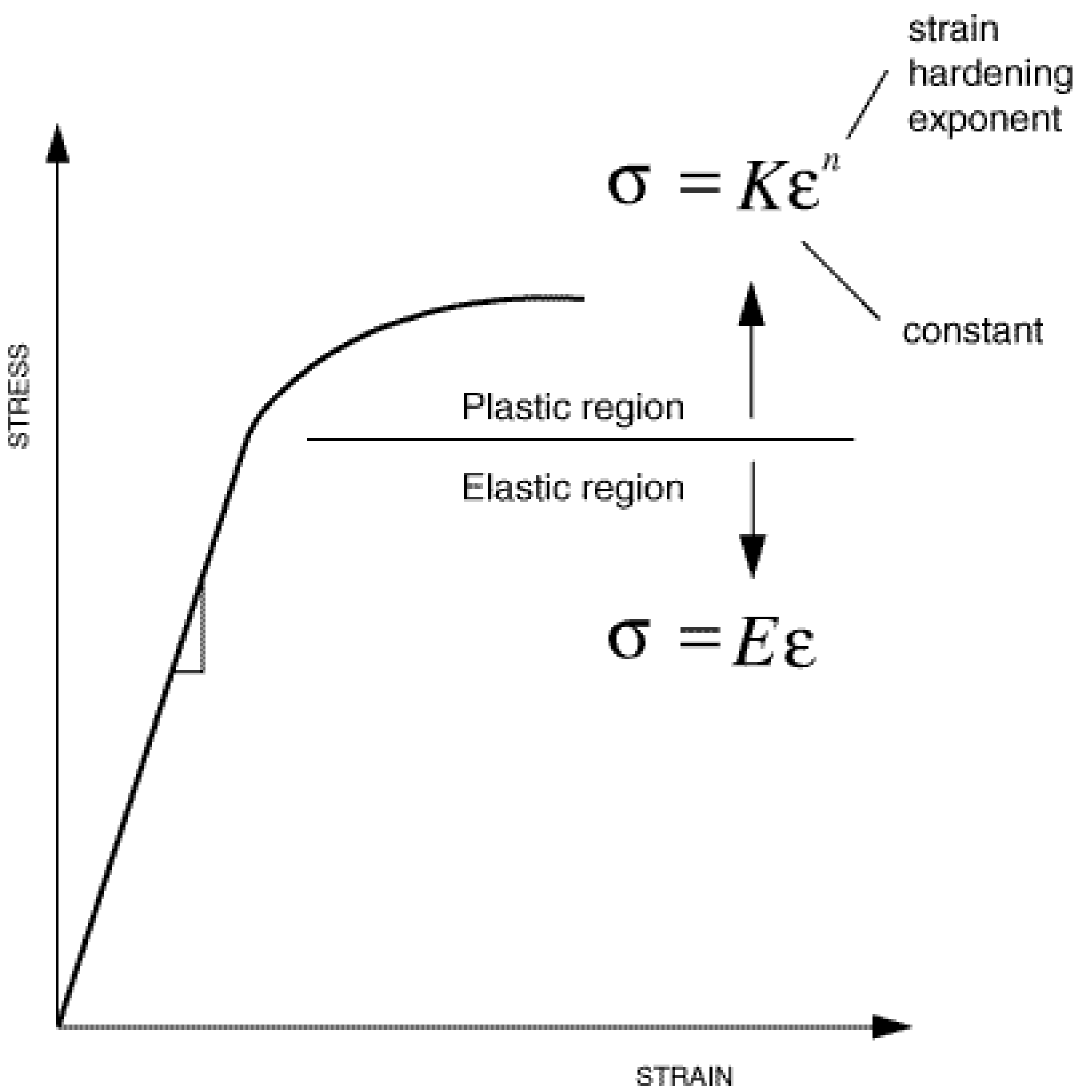


Figure 21b Figure 23

Table 11 - Strain Hardening Exponent

Brush Alloy	n	K (ksi)	(kg/mm^2)
25 A	0.49	176	124
25 1/4 H	0.17	137	96
25 H	0.07	170	120
190 HM	0.06	198	139
3 AT	0.13	167	117
174 HT	0.07	153	108

FIGURE 23: PERMANENT SET

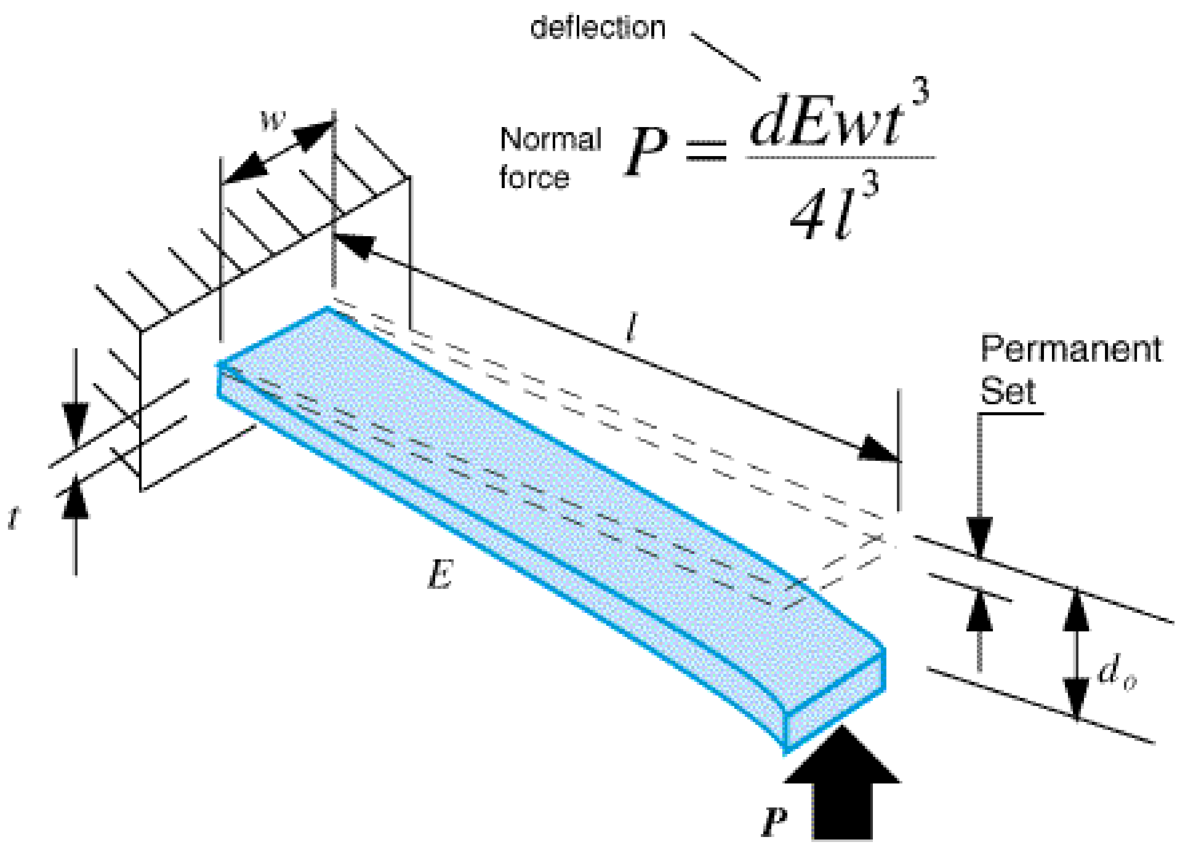


Figure 22 Figure 24a

FIGURE 24a: TOUGHNESS DEFINITION

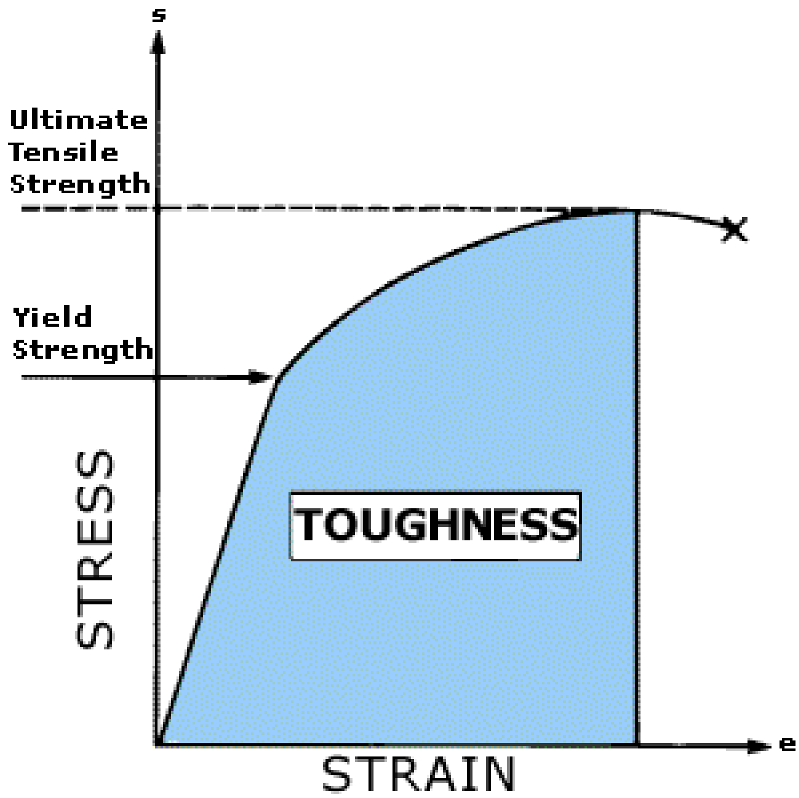


Figure 23 Figure 24b

FIGURE 24b: TOUGHNESS APPROXIMATION

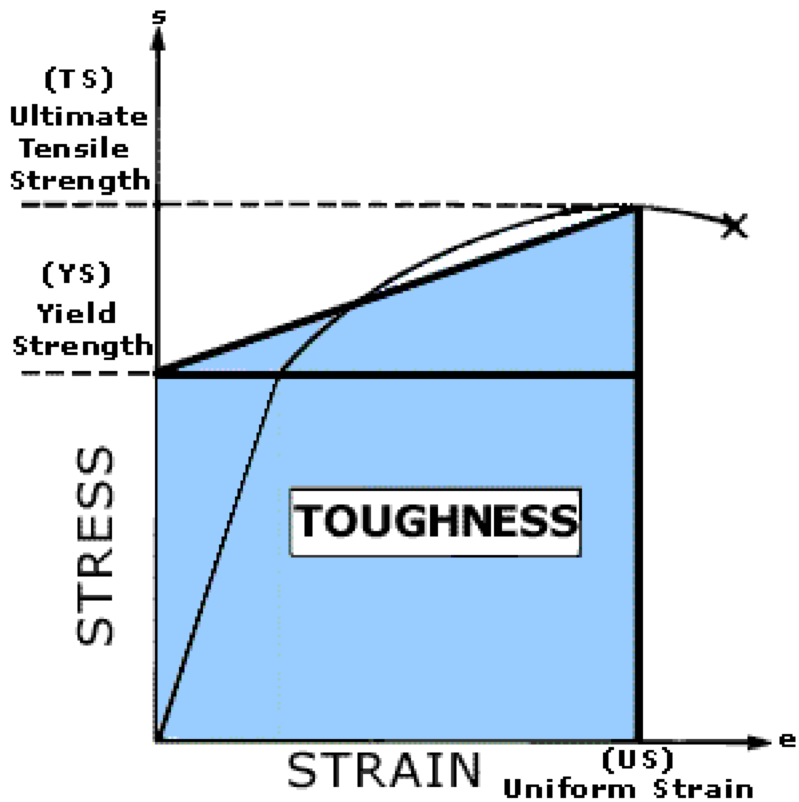
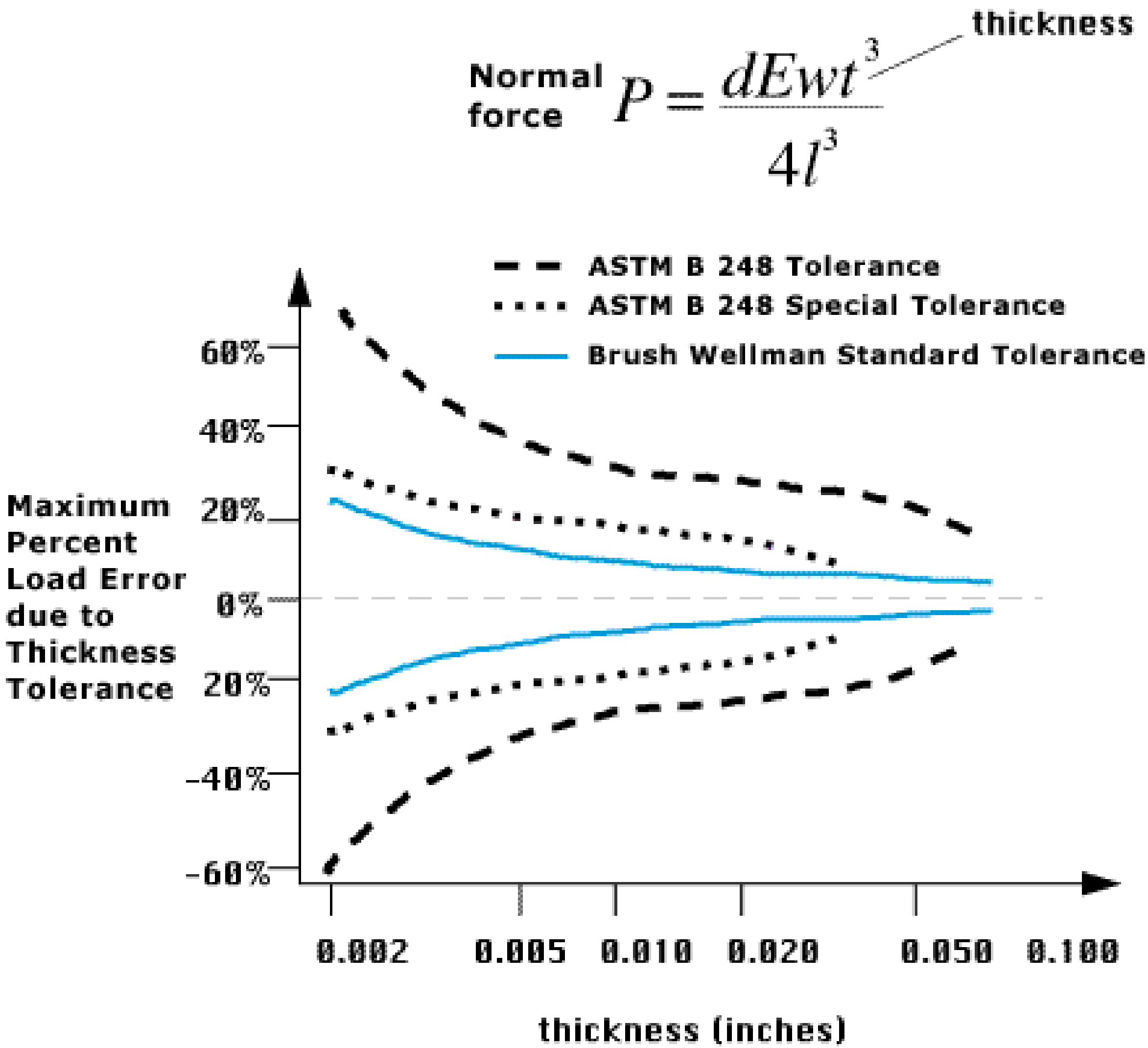


Figure 24a Figure 25

Table 12 - Thermal Expansion Coefficient

Alloy	**Thermal Expansion Coefficient (in/in/°F, 70°F to 400°F) (21°C to 204°C)**
25	9.7×10^{-6}
M25	
165	
3	9.8×10^{-6}
174	
260	11.1×10^{-6}
194	9.8×10^{-6}
510	9.9×10^{-6}
521	10.1×10^{-6}
688	
654	9.7×10^{-6}
725	9.2×10^{-6}

FIGURE 26: CONTACT LOAD ERROR DUE TO THICKNESS TOLERANCE



List of Figures

Figure 25 Figure 27

Design Guide
Figure 26

Table 14a - Strip Dimensional Tolerances

Strip Thickness (inches)	BRUSH STD Tolerance (+/- inches)	ASTM B 248 Special Tolerance (+/- inches)	ASTM B 248 STD Tolerance (+/- inches)
over - including			
0.0020 - 0.0040	0.00015	0.0002	0.0004
0.0040 - 0.0060	0.00020	0.0003	0.0006
0.0060 - 0.0090	0.00025	0.0004	0.0008
0.0090 - 0.0130	0.00030	0.0005	0.0010
0.0130 - 0.0170	0.00040	0.0007	0.0013
0.0170 - 0.0210	0.00040	0.0008	0.0015
0.0210 - 0.0260	0.00040	0.0010	0.0020
0.0260 - 0.0370	0.00060	0.0013	0.0025
0.0370 - 0.0500	0.00080	0.0015	0.0030
0.0500 - 0.0730	0.00100		0.0035

List of Tables

Table 13 Table14b

Design Guide - Table 14a

Table 14b - Strip Dimensional Tolerances (Metric)

Strip Thickness (mm)	BRUSH STD Tolerance (+/- mm)
0.05 - 0.10	0.0038
0.10 - 0.20	0.006
0.20 - 0.30	0.008
0.30 - 0.70	0.010
0.70 - 1.0	0.016
1.0 - 1.3	0.020
1.3 - 2.0	0.025

List of Tables

Table 14a Table15a

Design Guide - Table 14b

Table 15a - Wire Dimensional Tolerances

	Brush STD Tolerance*	
Wire Diameter (inches)	**Cold Drawn (+ /- inches)**	**Annealed (+ /- inches)**
0.0500 - 0.0800	0.0003	0.001
0.0800 - 0.1250	0.0004	0.002
0.1250 - 0.2500	0.0006	0.002
0.2500 - 0.3125	0.0007	0.002
0.3125 - 0.4060	0.0010	0.002
0.4060 - 0.5000	0.0010	0.002
*Note: Out of Round tolerance is half the diameter tolerance.		

List of Tables

Table 14b Table15b

Design Guide -
Table 15a

Table 15b - Wire Dimensional Tolerances (Metric)

	Brush STD Tolerance*	
Wire Diameter (mm)	**Cold Drawn (+ / - mm)**	**Annealed (+ / - mm)**
1.2 - 1.5	0.01	0.03
1.5 - 2.0	0.01	0.03
2.0 - 3.8	0.02	0.05
3.8 - 12%nbsp;	0.03	0.05
*Note: Out of Round tolerance is half the diameter tolerance.		

List of Tables

Table 15a Table 16

Design Guide - Table 15b

FIGURE 27:SUPPORT CONDITIONS

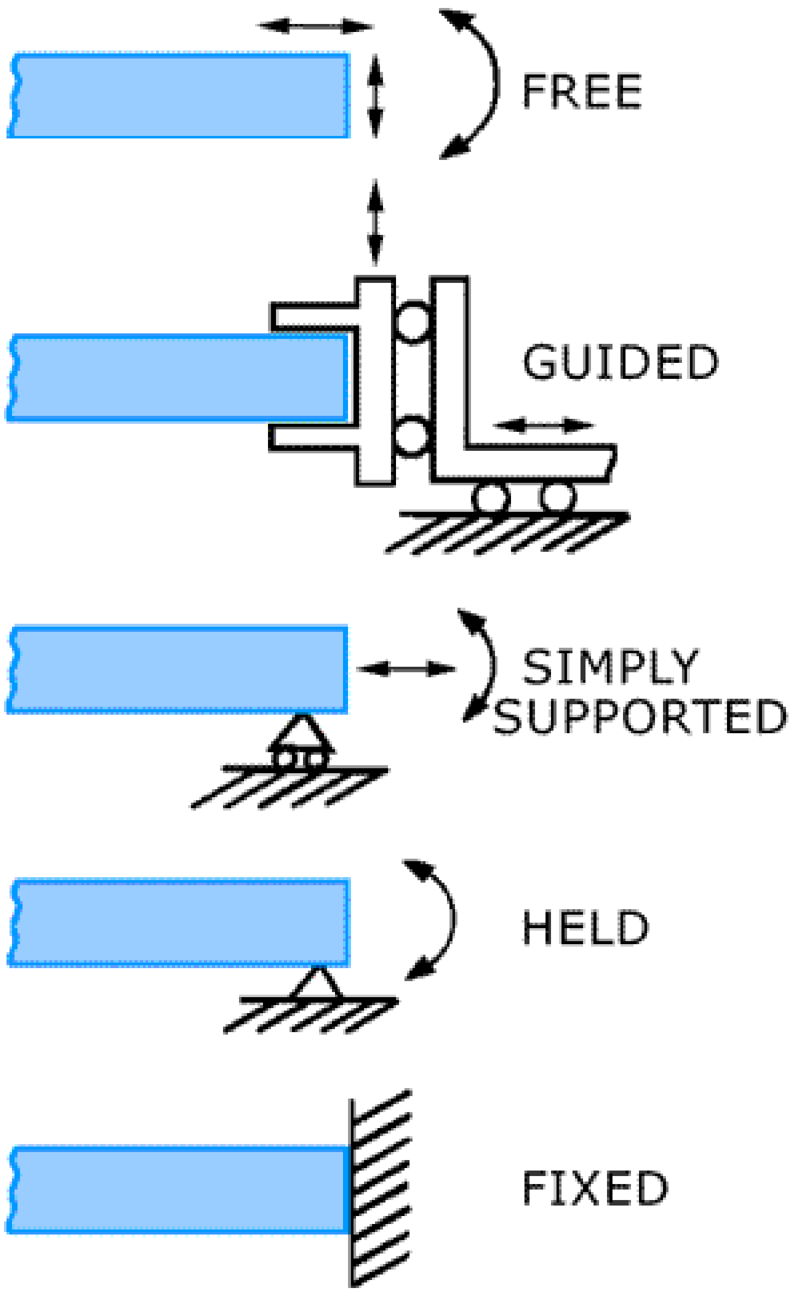


FIGURE 28:COMMON CROSS-SECTION PROPERTIES

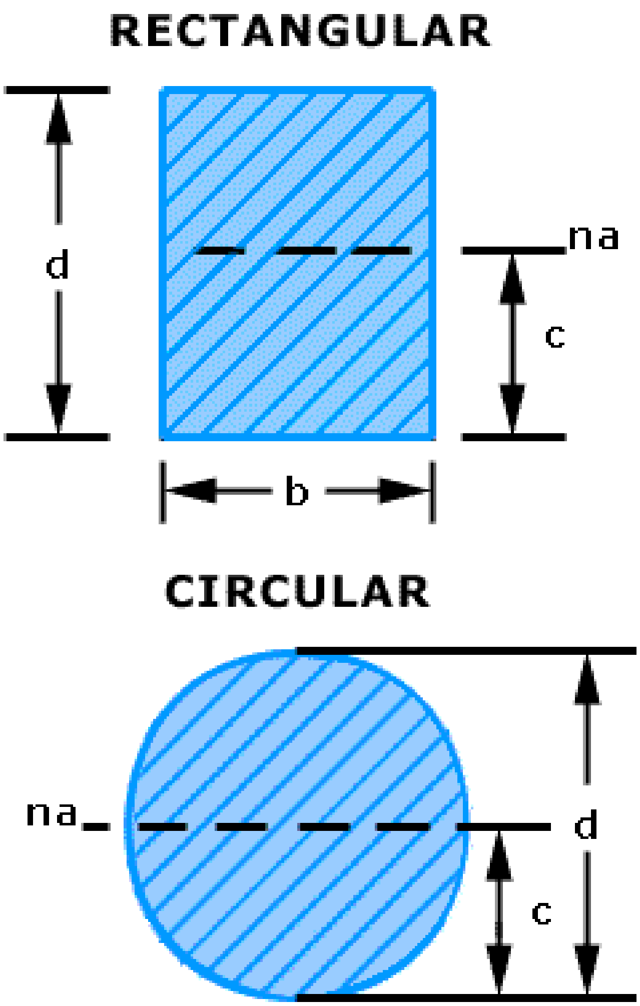
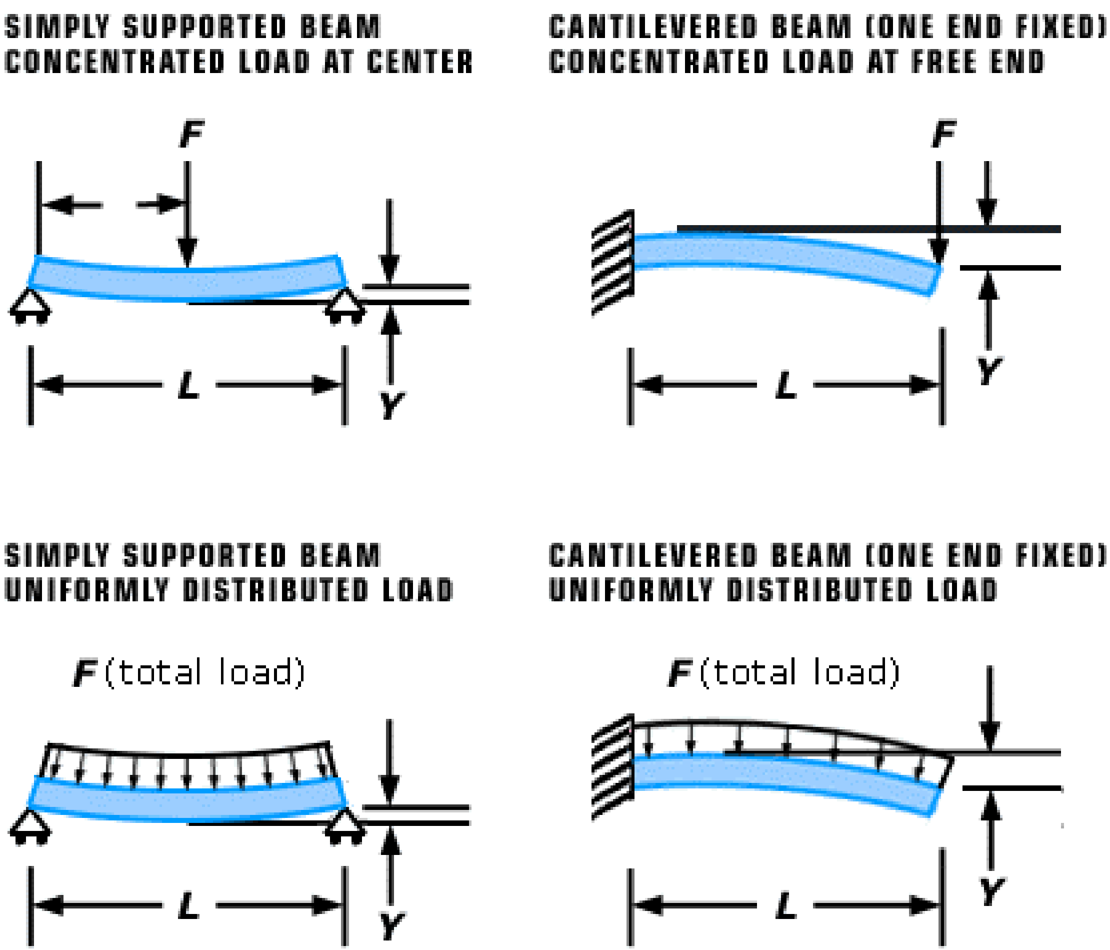


FIGURE 29: MAXIMUM STRESS AND DEFLECTION EQUATIONS

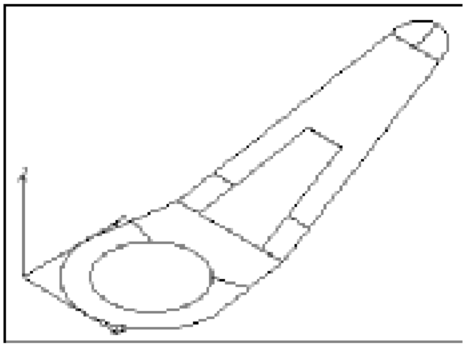


List of Figures

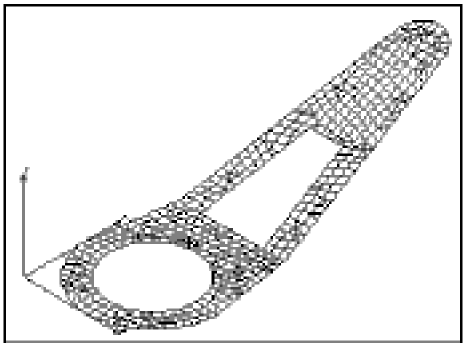
Figure 28 Figure 30a

Design Guide
Figure 29

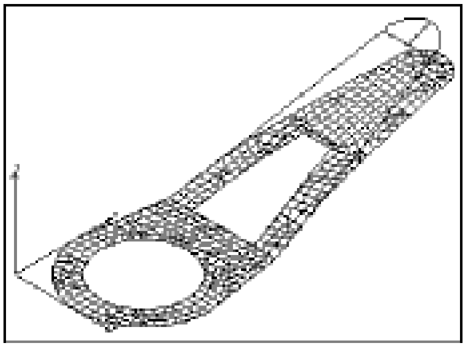
FIGURE 31: FINITE ELEMENT MODEL EXAMPLE



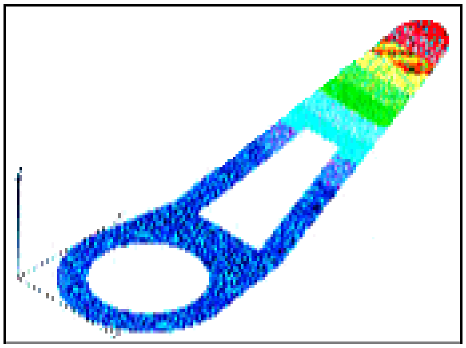
WIREFRAME GEOMETRY



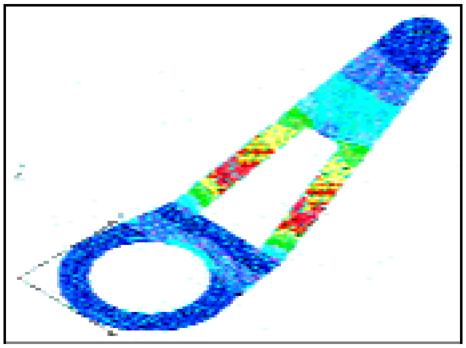
FEA MESH



DEFORMED SHAPE



DISPLACEMENT PLOT



VON MISES STRESS PLOT

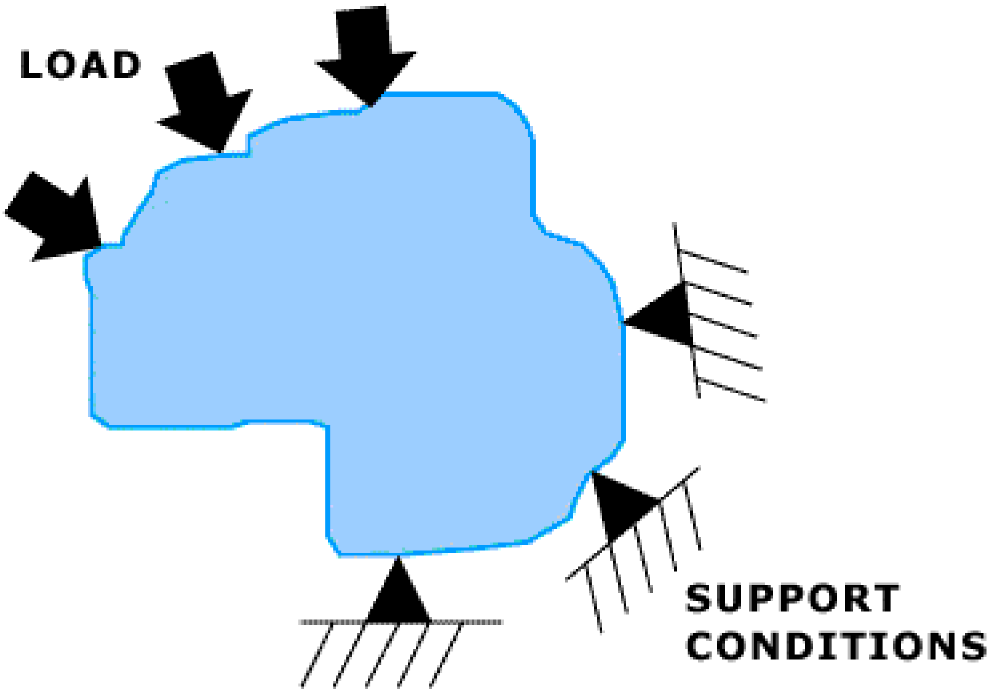
DESIGN & analysis

INDUSTRY TRENDS
▼
CONNECTOR REQUIREMENTS
▼
DESIGN & ANALYSIS ◀ MATERIAL PROPERTIES
▼
PROTOTYPE & VERIFICATION
▼
QUALIFICATION
▼
PRODUCTION

Finite Element Analysis

Finite Element Analysis (FEA) is a computer based technique for finding stresses and deflections in a structure using selected load cases. The method divides a structure into small elements with easily defined stress and deflection characteristics based on a series of differential equations. The finite element method solves these equations with global matrices using a computer program. FEA solves mechanical and thermal problems and models

FIGURE 30a: FINITE ELEMENT MODEL

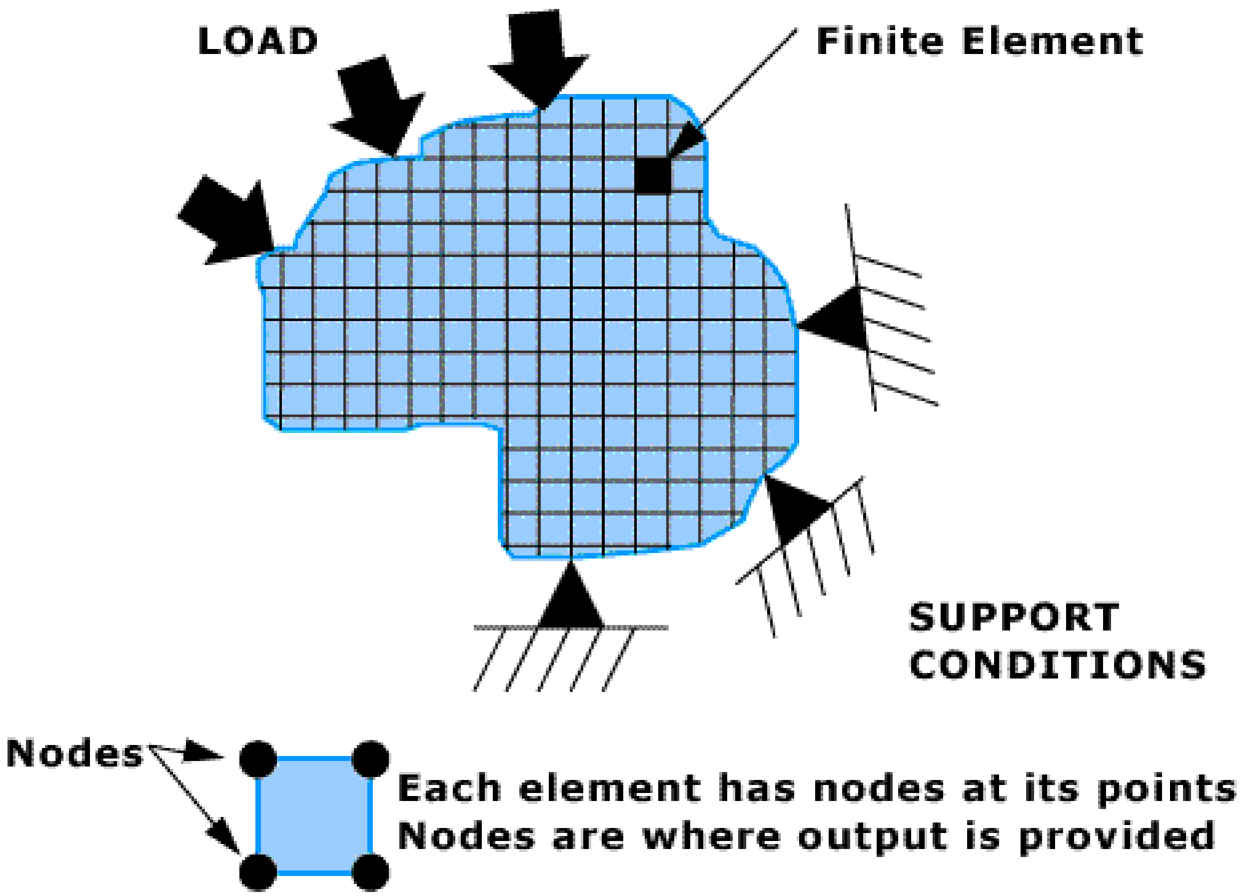


List of Figures

Figure 29 Figure 30b

Design Guide
Figure 30a

FIGURE 30b: FINITE ELEMENT MODEL



List of Figures

Figure 30a Figure 31

Design Guide
Figure 30b

Table 16 - Design Evaluation

Evaluation	Quantity Measured
Construction Analysis	Contact force Insertion/Extraction Force Plating Adhesion Plating Porosity
Metrology	Contact Spacing Housing Dimensions Contact Dimensions Plating Thickness Contact Geometry
Electrical Characterization	Contact Resistance Current Rating or Capacity Dielectric Strength
Assembly Compatibility	Process Thermal Stress Insulation Resistance Solvent Resistance
Safety Approval	UL Flammability

List of Tables

Table 15b Table 17

Design Guide - Table 16

Table 17 - Paired Date for Alloy 1/2 HT

Point	Strain	Stress (ksi)	Std. Dev. (ksi)	Secant Modulus
1	0.000000	0.00	0.00	
2	0.000606	10.09	6.44	16.6E+6
3	0.001414	24.39	7.42	17.2E+6
4	0.002222	40.87	6.54	18.4E+6
5	0.003030	56.55	6.54	18.7E+6
6	0.003838	72.29	5.20	18.8E+6
7	0.004646	87.72	2.89	18.9E+6
8	0.005455	102.64	3.03	18.8E+6
9	0.006263	117.17	3.16	18.7E+6
10	0.007071	131.02	3.34	18.5E+6
11	0.007172	132.70	3.32	18.5E+6
12	0.007273	134.36	3.28	18.5E+6
13	0.007374	136.00	3.23	18.4E+6
14	0.007475	137.60	3.22	18.4E+6
15	0.007576	139.17	3.21	18.4E+6
16	0.007677	140.72	3.21	18.3E+6
17	0.007778	142.24	3.22	18.3E+6
18	0.007879	143.73	3.23	18.2E+6
19	0.007980	145.19	3.21	18.2E+6
20	0.008081	146.63	3.17	18.1E+6
21	0.008182	148.04	3.14	18.1E+6
22	0.008283	149.41	3.13	18.0E+6
23	0.008384	150.75	3.13	18.0E+6
24	0.008485	152.04	3.13	17.9E+6
25	0.008586	153.29	3.11	17.9E+6
26	0.008687	154.54	3.08	17.8E+6
27	0.008788	155.75	3.04	17.7E+6
28	0.008889	156.92	3.02	17.7E+6
29	0.008990	158.05	3.00	17.6E+6
30	0.009091	159.13	3.00	17.5E+6
31	0.009192	160.19	2.99	17.4E+6
32	0.009293	161.21	2.99	17.3E+6
33	0.009394	162.19	2.98	17.3E+6
34	0.009495	163.15	2.98	17.2E+6
35	0.009596	164.08	2.97	17.1E+6
36	0.009697	164.98	2.94	17.0E+6
37	0.009798	165.86	2.94	16.9E+6
38	0.009899	166.69	2.94	16.8E+6
39	0.010000	167.49	2.95	16.7E+6
40	0.012513	180.82	2.75	14.5E+6
41	0.015026	187.40	2.79	12.5E+6
42	0.017538	190.80	2.78	10.9E+6
43	0.020051	191.79	12.26	9.6E+6
44	0.022564	191.30	20.89	8.5E+6

Table 18 - Test Methods

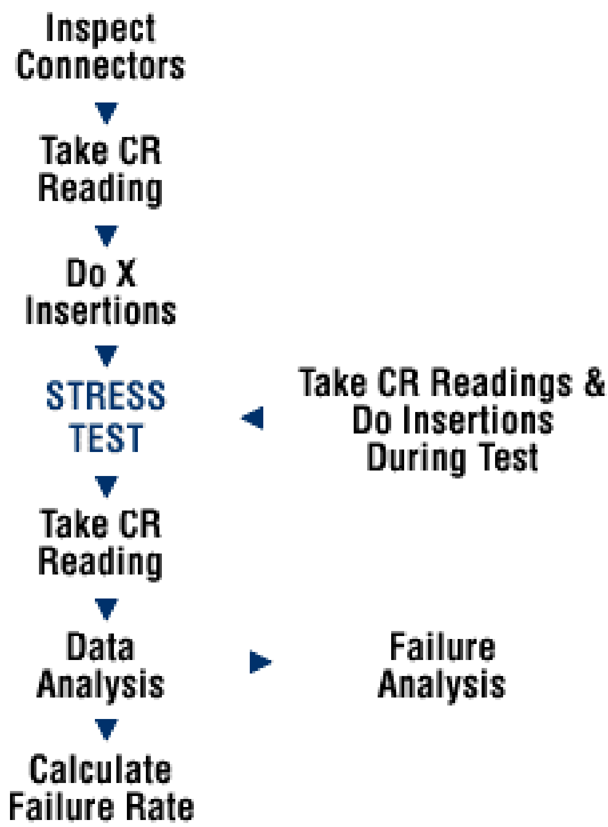
Date Required	Test Method
Tensile Test Properties	ASTM E 8
Hardness (Vickers or DPH)	ASTM E 384
Grain Size	ASTM E 112
Electrical Resistivity	ASTM B 193
Formability	ASTM E 290
Stress Relaxation	ASTM E 328 Part C-3
Solderability	MIL STD 202 Method 208

List of Tables

Table 17 Table 19

Design Guide - Table 18

FIGURE 33: STRESS TEST METHOD



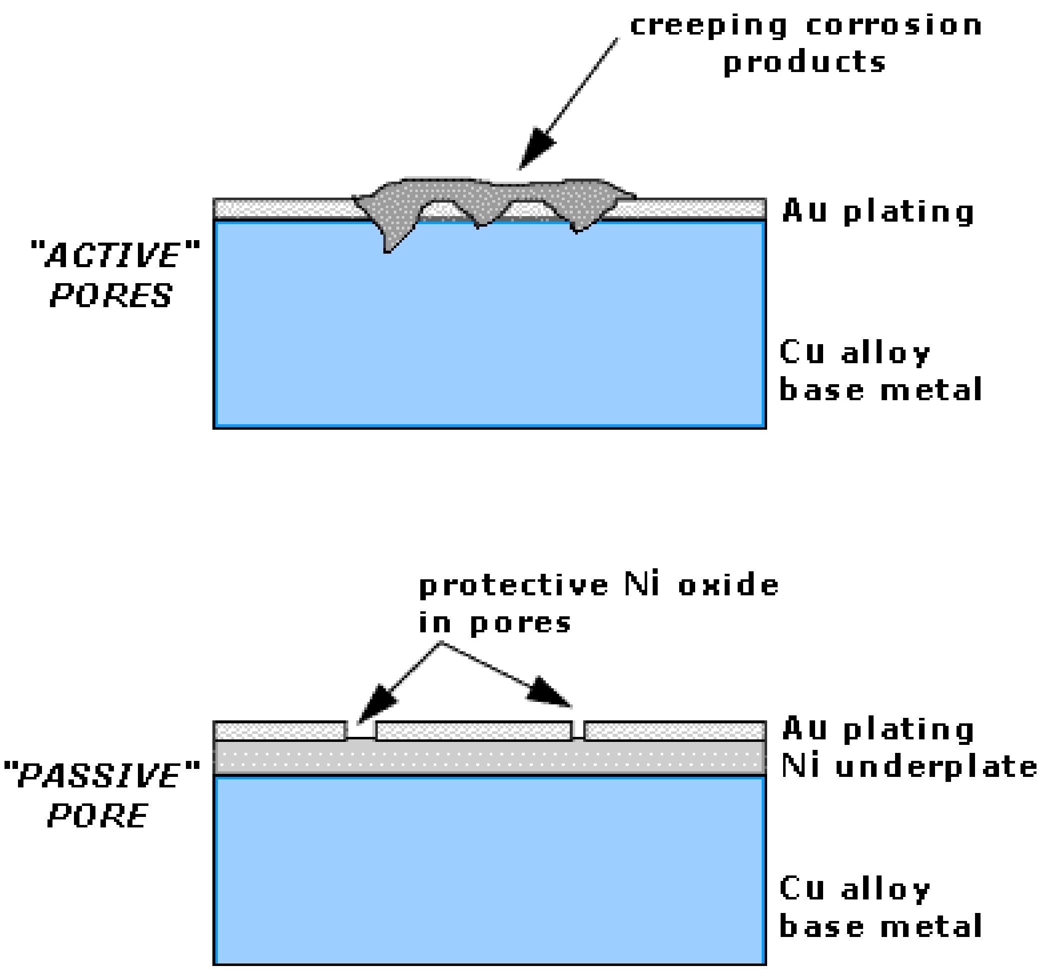
List of Figures

Figure 32 Figure 34

Design Guide
Figure 33

Section VII: Production
Table of Contents Detail

FIGURE 34:PORE CORROSION

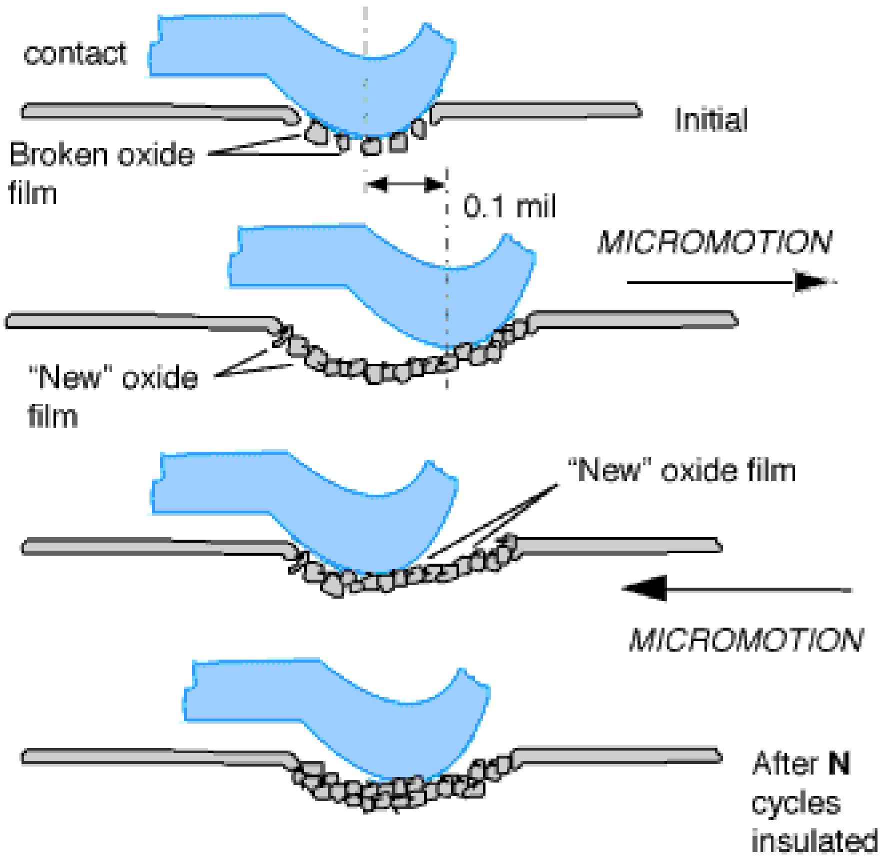


[List of Figures]

[Figure 33] [Figure 35]

[Design Guide]
[Figure 34]

FIGURE 35:FRETTING CORROSION

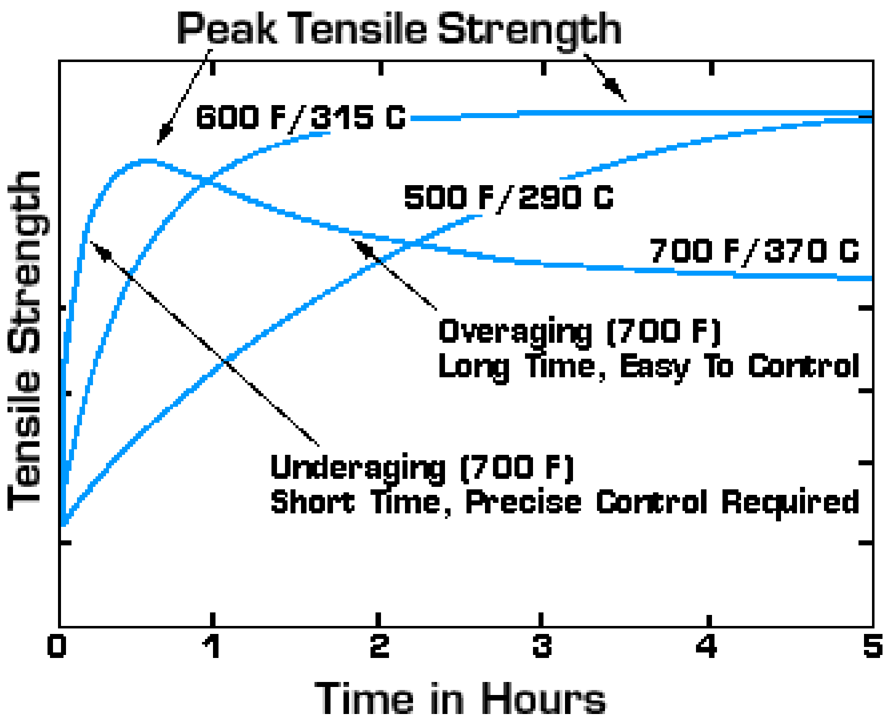


List of Figures

Figure 34 Figure 36

Design Guide
Figure 35

FIGURE 39: RESPONSE TO AGE HARDENING LOAD CASES (ALLOY 25)

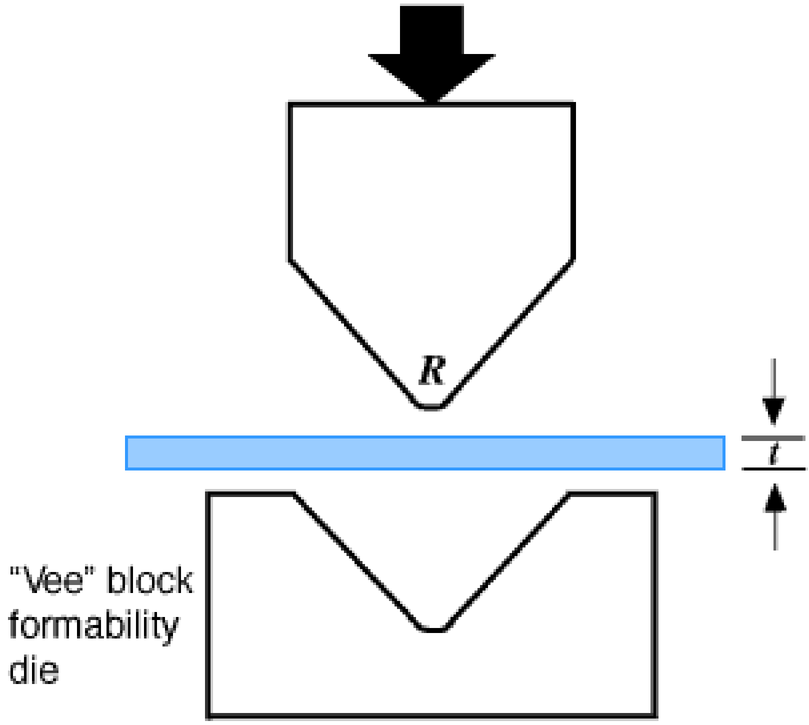


List of Figures

Figure 38 Figure 40

Design Guide
Figure 39

FIGURE 36: VEE BLOCK FORMABILITY DIE

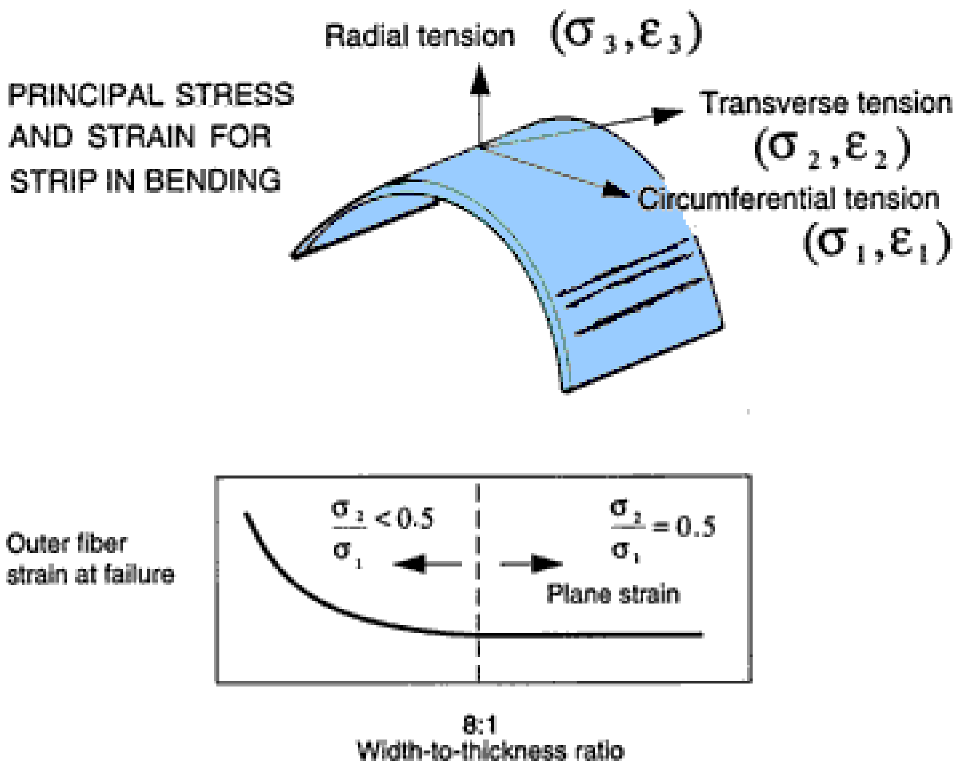


List of Figures

Figure 35 Figure 37

Design Guide
Figure 36

FIGURE 37:FORMABILITY WIDTH DEPENDENCE

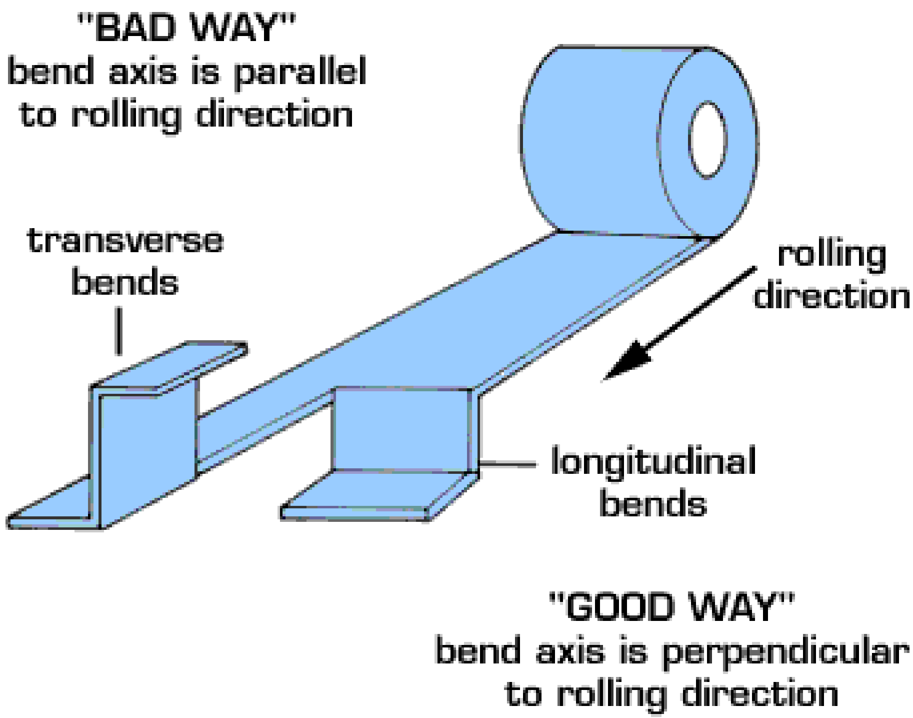


List of Figures

Figure 36 Figure 38

Design Guide
Figure 37

FIGURE 38: BENDING DIRECTIONS



List of Figures

Figure 37 Figure 39

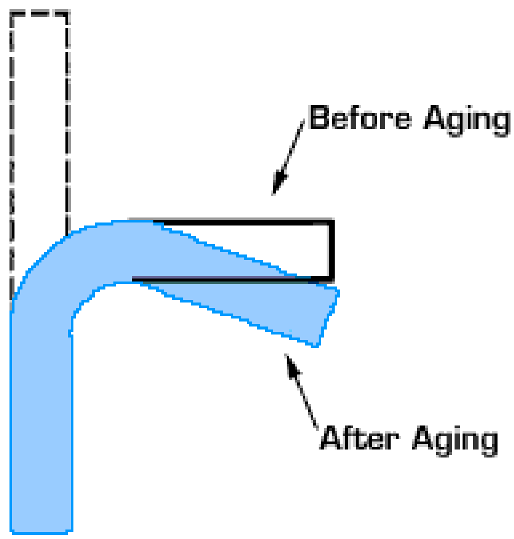
Design Guide
Figure 38

Table 19 - Formability

Alloy	Temper	Formability (Min. R/t for 90° Bend) Longitudinal	Transverse
25	A	0	0
	1/4 H	0	0
	1/2 H	0.5	1.0
	H	1	2.9
	1/4 HT	-	-
	1/2 HT	-	-
	H	-	-
190	AM	0.0	0
	1/4 HM	0.5	0.5
	1/2 HM	0.5	1.0
	HM	2.0	2.0
	SHM	2.8	3.2
	XHM	4.0	5.0
	XHMS	5.0	10.0
290	TM00	0	0
	TM02	0	0
	TM04	1.0	1.0
	TM06	2.5	2.0
	TM08	3.5	3.0
60	3/4 HT	0.7	0.7
	HT	1.5	1.5
199	EHP	1.0*	4.0*
	SHP	0.0*	1.0*
	ESHP	0.0*	2.0*
3	A	0	0
	H	0.5	0.5
	AT	1.0	1.0
	HT	2.0	2.0
174	1/2 HT	0.5	0.5
	HT	1.2	5.0
260	H	1.0	1.5
194	S	-	-
510	1/2H	0	2
	H	0.5	3
	S	3	8
521	1/2 H	0	2
	H	0.5	3
	S	2	7
654	1/2 H	1	1
	H	2	3
	S	4	7
	XS	5	8
688	1/2H	1	1
	H	2.5	3
	S	5	6
	XS	6	9
7025	TM02	2.5	1.5
	TM03	2.5	2
725	1/2 H	2	2
	H	3	3
	S	4	6

* = "W" bend

FIGURE 40: VOLUME CONTRACTION DUE TO AGE HARDENING

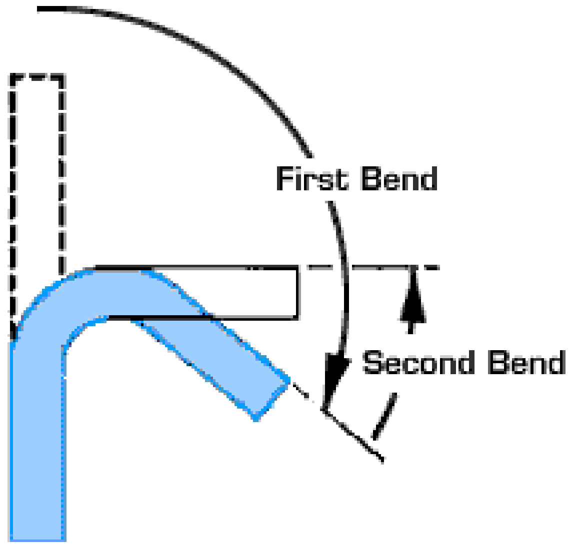


List of Figures

Figure 39 Figure 41

Design Guide
Figure 40

FIGURE 41: TWO-STEP BEND PROCESS



List of Figures

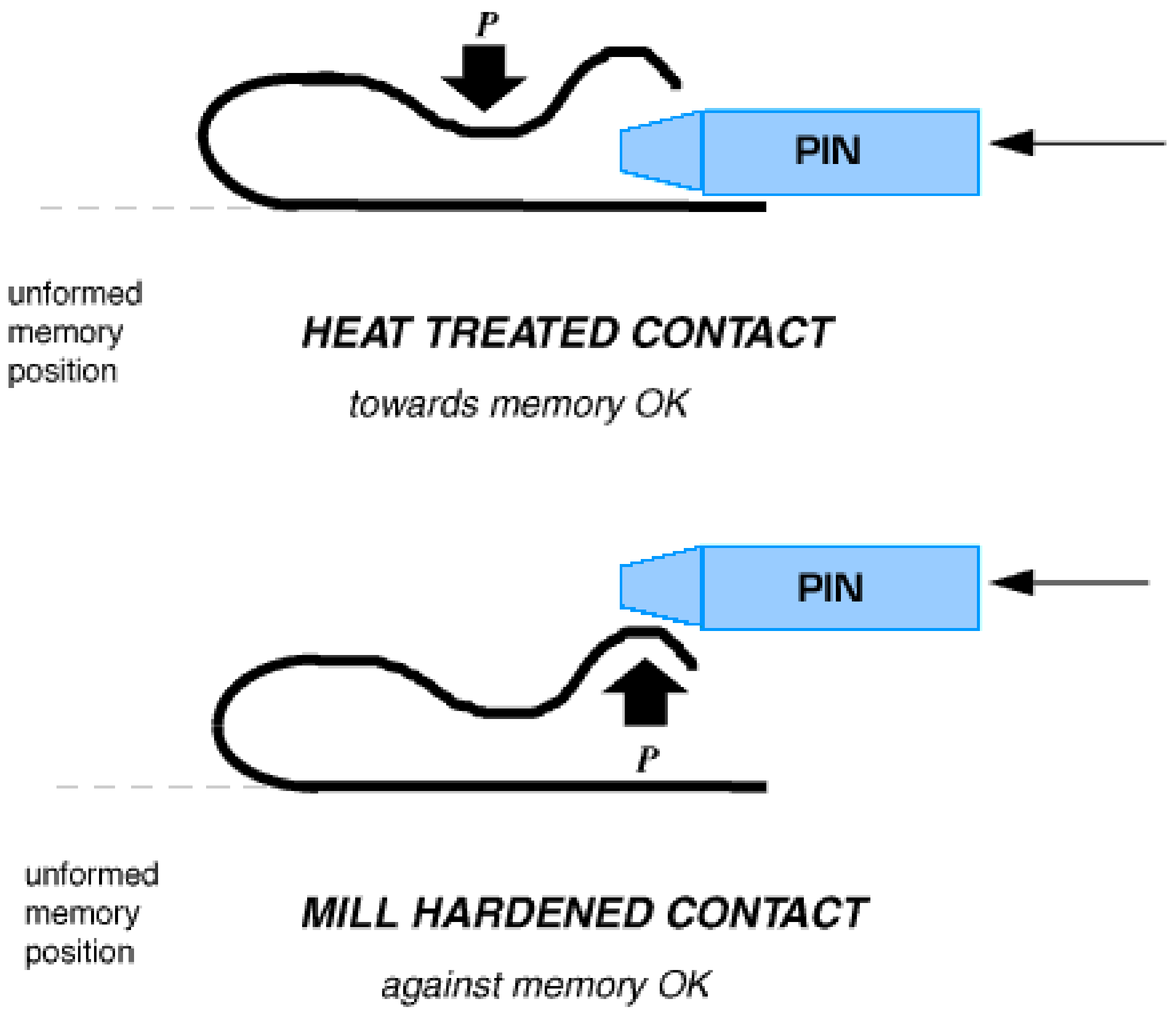
Figure 40 Figure 42

Design Guide
Figure 41

Table 20 - Heat Treatable vs. Mill Hardened

Property	Heat Treatable	Mill Hardened
Processing	Rolled, formed, heat treated Best possible formability	Heat treated, rolled, formed
Formability	Formed and then heat treated	Heat treated before forming
Grain Direction	Nearly isotropic properties since heat treating stress relieves rolling	Transverse direction has limited formability for higher tempers
Residual Stress	Responds equally to applied strain regardless of direction	Contains residual rolling stresses. Limited load capacity in unbending direction. (Figure 42)
Stability	Minimal stress relaxation at elevated temperatures	Subject to stress relaxation due to residual stresses
Heat Treatment Distortion	Shrinkage during heat treatment	No shrinkage since formed after heat treatment
Plating	Post plated after heat treatment	Can be plated before or after forming

FIGURE 42:HEAT TREATED VS. MILL HARDENED LOAD CASES

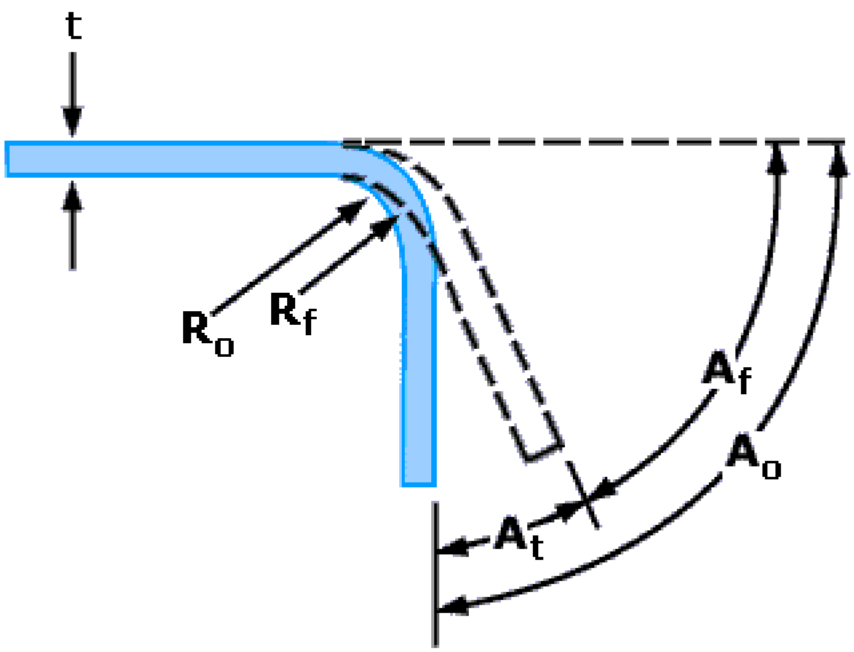


List of Figures

Figure 41 Figure 43

Design Guide
Figure 42

FIGURE 43:SPRINGBACK OF FORMED STRIP



List of Figures

Figure 42 Figure 44

Design Guide
Figure 43

Table 21 - Machinability Rating

Alloy	Machinability Rating (Free Machining Brass = 100)
25	35
M25	40
3	25
510	20
521	20
534	45
654	30
1915	75

List of Tables
Table 20 Table 22
Design Guide - Table 21

Table 22 - Rod Mechanical Properties

		Yield Strength 0.2%		Tensile Strength		Elongation (%) min.
Alloy	**Temper**	**(ksi)**	**(kg/mm^2)**	**(ksi)**	**(kg/mm^2)**	
25, M25	A	20-35	14-25	60-85	42-60	20
	H	75-105	53-74	90-130	63-91	8
	AT	145-175	102-123	165-200	116-141	4
	HT	160-200	112-141	185-225	130-158	2
165	A	20-35	14-25	60-85	42-60	20
	H	75-105	53-74	90-130	63-91	8
	AT	125-155	88-109	150-190	105-134	4
	HT	145-185	102-130	170-210	120-148	2
3,10	A	10-30	7-21	35-55	25-39	20
	H	50-75	35-53	65-80	46-56	10
	AT	80-100	56-70	100-130	70-91	10
	HT	95-125	67-88	110-140	77-98	5
1915	A	10-40	7-28	30-50	21-35	35
	H	45-70	32-49	55-75	39-53	5
	AT	25-50	18-35	25-50	18-35	20
	HT	70-95	49-67	85-105	60-74	4

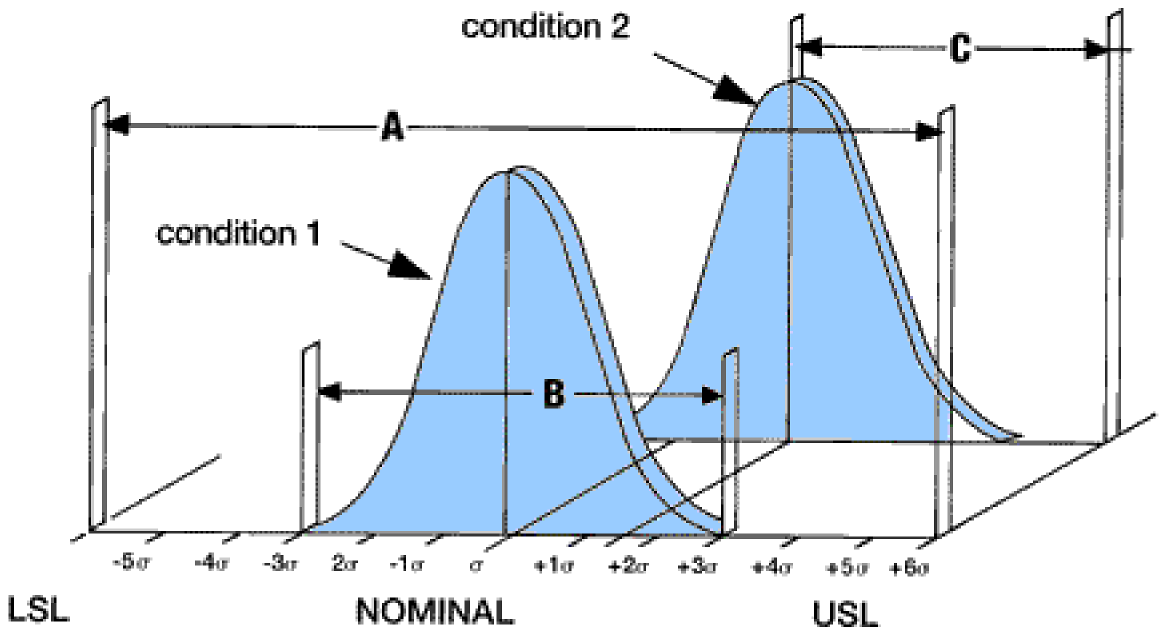
Table 23 - Wire Mechanical Propertie
(Wire Diameters from 0.050 inch [1.27mm]
to 0.375 inch [95.5 mm]

Alloy	Temper	Yield Strength 0.20% (ksi)	Yield Strength 0.20% (kg/mm^2)	Tensile Strength (ksi)	Tensile Strength (kg/mm^2)	Elongation (%) min.
25, M25	A	20-35	14-22	58-78	42-55	30
	1/4 H	75-105	52-74	90-115	63-81	3
	1/2 H	90-125	63-88	110-135	77-95	2
	3/4 H	115-150	80-106	130-155	91-109	2
	H	130-160	91-113	140-165	98-117	1
	AT	145-180	101-127	160-200	112-141	3
	1/4 HT	165-200	116-141	175-210	123-148	2
	1/2 HT	170-210	119-148	185-215	130-152	2
	3/4 HT	175-220	123-155	190-230	133-162	2
	HT	180-220	126-155	195-230	137-162	1
3,10	A	10-30	7-22	35-55	24-39	20
	H	55-75	38-53	65-80	45-57	2
	AT	80-110	56-78	100-130	70-92	10
	HT	95-125	66-88	110-140	77-99	10
510, 534	1/2 H	75-92	53-65	80-97	56-68	8
	H	103-122	72-86	108-128	76-90	5
	S	130 min	91 min	135 min	95 min	2
521	1/2H	80-105	56-74	95-115	67-81	10
	H	120-145	84-102	125-150	88-105	3
	S	135 min	95 min	140 min	98 min	2
1915	A	5-25	4-18	25-50	18-35	40
	H	35-65	25-46	50-75	35-53	4
	AT	25-50	18-35	50-70	35-49	25
	HT	75-100	53-70	85-105	60-74	4
725	H	88	62	95-110	67-77	5
	S	82	58	110-125	77-88	3

FIGURE 44: CONCEPTS UNDERLYING C_p AND C_{pk}

condition 1: Distribution average centered on nominal specification

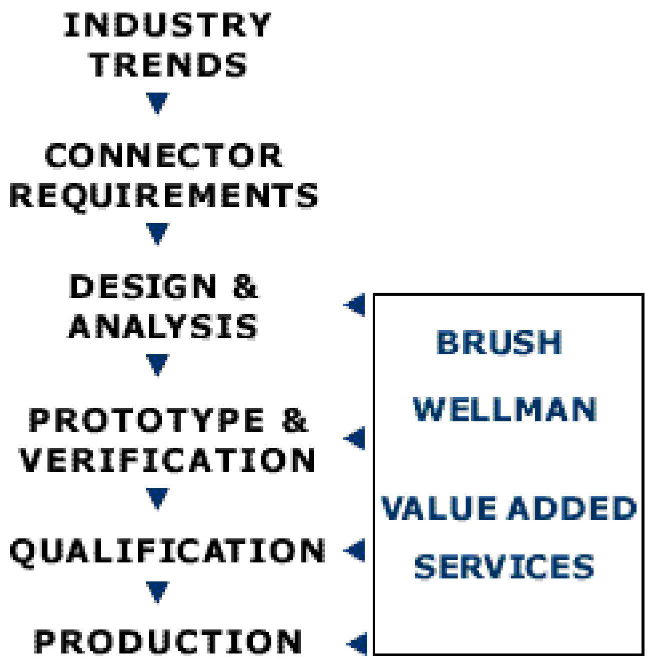
condition 2: Distribution average shifted 1.5 sigma from the nominal specification



CAPABILITY	condition 1	condition 2
C_p = A/B	2.0	2.0
C_{pk} = C/0.5B	2.0	1.5

DESIGN & analysis

Design Review



Prior to the prototyping stage, design reviews ensure that the original requirements of the connector are achievable. An available resource is Brush Wellman's services including design assistance, technical service and a worldwide distribution network.

Brush Wellman Services

Alloy selection -- With more than 200 strip metals listed by the Copper Development Association (CDA), paring those down to a handful with the proper attributes is useful to connector design engineers.

Design assistance -- Brush Wellman has the resources to perform simple stress calculations as sanity checks as well as in-house capability to perform more complex Finite Element Modeling.

Toll free customer service -- **1-800-375-4205** -- technical service staff
(or, if you prefer, email us)

Technical staff -- Research and development organization

Technical specialists -- Application specific specialist to assist with design and fabrication

Literature -- Current literature is available for each product

Library -- Technical library with electronic database systems

Educational seminars -- BeCu Update seminars as well as in-house specific seminars.

Custom fabrication -- Capabilities and engineering facility in Elmore plant

Failure analysis -- Both the Cleveland and Reading laboratories are available to perform routine failure analysis on the material.

Worldwide network -- Brush Wellman maintains a worldwide network to guarantee on time delivery of base metal that consist of the following:

- *Service Centers* (material stocking)

  - Domestic -- New Jersey, Michigan, Illinois, California
  - Foreign -- Japan, England, Germany

- *Independent distributors*

- *Authorized agents*

Reprocessor relationships -- Through our relationship with alloy reprocessors we can provide a direct link to special customer needs. The list below describes alloy reprocessors:

- Re-rollers (foil thickness < 0.003 inches [0.08 mm])

- Wire re-drawers (wire diameter < 0.050 inches [1.27 mm])

- Tubing re-drawers (tube diameter < 0.75 inches [19.05 mm])

Technical Exchange

List of Figures | List of Tables

Introduction

Technical Exchange

Design Guide - Table of Contents

Design Guide - List of Charts

Design Guide

Table 1 - Operating Environments

Use Category	T min (°F)	T min (°C)	T max (°F)	T max (°C)	Years of Service
Consumer	+32	0	140	+60	1-3
Computers	+59	+15	140	+60	≈5
Telecom	-40	-40	185	+85	7-20
Commercial Aircraft	-67	-55	203	+95	≈20
Industrial & Automotive Passenger Compartment	-67	-55	203	+95	≈10
Military Ground & Ship	-67	-55	203	+95	≈5
Space LEO & GEO	-40	-40	185	+85	5-20
Military Avionics	-67	-55	203	+95	≈10
Automotive Underhood	-67	-55	347	+175	≈10

	S	82	58	110-125	77-88	3

List of Tables

Table 22 Table 24

Design Guide - Table 23

	1/2 HM	1.9	2.2
	HM	3.8	5.1
	SHM	5.0	7.7
	XHM	6.1	10.4
3	A	0	0
	H	0.5	0.5
	AT	1.0	1.0
	HT	2.0	2.0
	HTR	2.8	3.5
	HTC	1.0	1.0
174	1/2 HT	0.5	0.5
	HT	1.2	5.0
260	H	1.0	1.5
194	S	-	-
510	1/2 H	0	2
	H	0.5	3
	S	3	8
521	1/2 H	0	2
	H	0.5	3
	S	2	7
654	1/2 H	1	1
	H	2	3
	S	4	7
	XS	5	8
688	1/2 H	1	1
	H	2.5	3
	S	5	6
	XS	6	9
7025	TM02	2.5	1.5
	TM03	2.5	2
725	1/2 H	2	2
	H	3	3
	S	4	6

List of Tables

Table 18 Table 20

Design Guide -
Table 19

27	161516	9008	596	17.93
28	168646	9740	923	17.28
29	172719	10186	1142	16.96
30	176793	10802	1505	16.37
31	179848	11210	1736	16.04
32	181885	11532	1938	15.77
33	182904	11784	2129	15.52

List of Tables

Table 16 Table 18

Design Guide - Table 17

	AM	40-45	28-32
	1/4 HM	40-45	28-32
	1/2 HM	42-48	30-34
	HM	45-52	32-37
	SHM	47-55	33-39
	XHM	50-57	35-40
3, 10	A	20-30	14-21
	H	25-35	18-25
	AT	38-44	27-31
	HT	42-47	30-33
	HTR	43-48	30-34
	HTC	30-35	21-25
174	1/2 HT	45-50	32-35
	HT	45-50	32-35
260	H	21	15
194	S	21	15
510	S	30	21
521	S	33	23
654	S	37	26
688	S	37	26
725	S	38	27

3	AT	94	72
	HT	96	75
	HTR	96	75
	HTC	94	72
174	1/2 HT	94	70
	HT	95	76
260	H	41	8
194	S	-	-
510	1/2 H	85	-
	H	83	-
	S	77	20
521	1/2 H	88	-
	H	83	-
	S	75	-
654	S	72	-
688	S	72	10
725	S	89	40

	1/4 HT	343-393	C35-40	30N55-59
	1/2 HT	363-413	C37-42	30N57-60
	HT	372-435	C38-44	30N58-63
	AM	225-251	B98-C23	30N37-44
	1/4 HM	230-271	C20-26	30N41-47
	1/2 HM	257-301	C24-30	30N45-51
	HM	285-343	C28-35	30N48-55
	SHM	309-363	C31-37	30N52-56
	XHM	317-378	C32-38	30N52-58
3, 10	A	65-125	B20-45	30T28-45
	H	144-176	B78-88	30T69-75
	AT	195-275	B92-100	30T77-82
	HT	216-287	B95-102	30T79-83
	HTR	216-287	B98-103	30T80-84
	HTC	147-176	B79-88	30T69-75
174	1/2 HT	180-230	B89-98	30T75.5-81.9
	HT	210-278	B95-C27	30T79-30N48

	H				90-115	63-81	100-120	70-85	2
	AT	3 hr at 600F			130-165	91-117	150-180	105-127	3
	1/4 HT	2 hr at 600F			135-175	94-124	160-190	112-134	3
	1/2 HT	2 hr at 600F			150-180	105-127	170-200	119-141	1
	HT	2 hr at 600F			155-180	108-127	180-210	126-148	1
	AM	Mill			70-95	49-67	100-110	70-78	18
	1/4 HM	Hardened			80-110	56-78	110-120	77-85	15
	1/2 HM				95-125	66-88	120-135	84-95	12
	HM				110-135	77-95	135-150	95-106	9
	SHM				125-140	87-99	150-160	106-113	9
	XHM				135-165	94-117	155-175	108-124	3
3, 10	A	-	20	14	20-45	19-39	35-55	25-39	20
	H	-			55-80	42-57	70-85	49-60	2
	AT	3 hr at 900F			80-100	56-71	100-130	70-92	10
	HT	2 hr at 900F			95-120	66-85	110-135	77-95	8
	HTR	Mill Hard			110-140	77-99	120-150	84-106	1
	HTC	Mill Hard			50-75	35-53	75-85	52-60	8
174	1/2 HT	Mill Hard	20	14	80-100	56-70	95-115	67-80	10
	HT				100-120	70-84	110-130	77-91	7
260	H	Not Age	16	11.3	60-75	42-53	71-81	50-57	6
		Hardenable							
194	S	Not Age	17.5	12.3	67-74	47-52	70-76	49-53	1
		Hardenable							
510	1/2 H	Not Age	16	11	47-68	33-48	58-73	41-51	16
	H	Hardenable			74-88	52-62	76-91	53-64	10
	S				92-108	65-76	95-110	67-77	4
521	1/2 H	Not Age	16	11	51-75	36-53	69-84	49-59	25
	H	Hardenable			78-95	55-67	85-100	60-70	12
	S				100-113	70-79	105-119	74-84	3
654	1/2 H	Not Age	17	12	66-92	46-65	86-101	60-71	11
	H	Hardenable			94-109	108-120	108-120	76-84	4
	S				112-123	80-86	124-133	87-94	2
	XS				118-131	83-92	131-140	92-98	1
688	1/2 H	Not Age	17	12	82-102	58-72	97-112	68-79	9
	H	Hardenable			95-108	67-76	106-120	75-84	4

	S				111-117	78-82	123-133	86-94	1
	XS				117 min	78 min	130 min	91 min	2 max
7025	TM02	Mill Hard	19	13.5	85-110	60-77	95-120	67-84	7
	TM03				95-120	67-84	100-125	70-88	5
725	1/2 H	Not Age	20	14	59-78	41-55	65-80	46-56	6
	H	Hardenable			73-88	51-62	75-90	53-63	3
	S				83-97	58-68	85-100	60-70	1

TABLE 15a - WIRE DIMENSIONAL TOLERANCES

	Brush STD Tolerance*	
Wire Diameter (inches)	**Cold Drawn (+ / - inches)**	**Annealed (+ / - inches)**
0.0500 - 0.0800	0.0003	0.001
0.0800 - 0.1250	0.0004	0.002
0.1250 - 0.2500	0.0006	0.002
0.2500 - 0.3125	0.0007	0.002
0.3125 - 0.4060	0.0010	0.002
0.4060 - 0.5000	0.0010	0.002

*Note: Out of Round tolerance is half the diameter tolerance.

TABLE 15b - WIRE DIMENSIONAL TOLERANCES (METRIC)

	Brush STD Tolerance*	
Wire Diameter (mm)	**Cold Drawn (+ / - mm)**	**Annealed (+ / - mm)**
1.2 - 1.5	0.01	0.03
1.5 - 2.0	0.01	0.03
2.0 - 3.8	0.02	0.05
3.8 - 12	0.03	0.05

*Note: Out of Round tolerance is half the diameter tolerance.

Technical Exchange

Section V: Design & Analysis

Section V: Design & Analysis Structural Analysis

Design Guide - Table of Contents

Technical Exchange

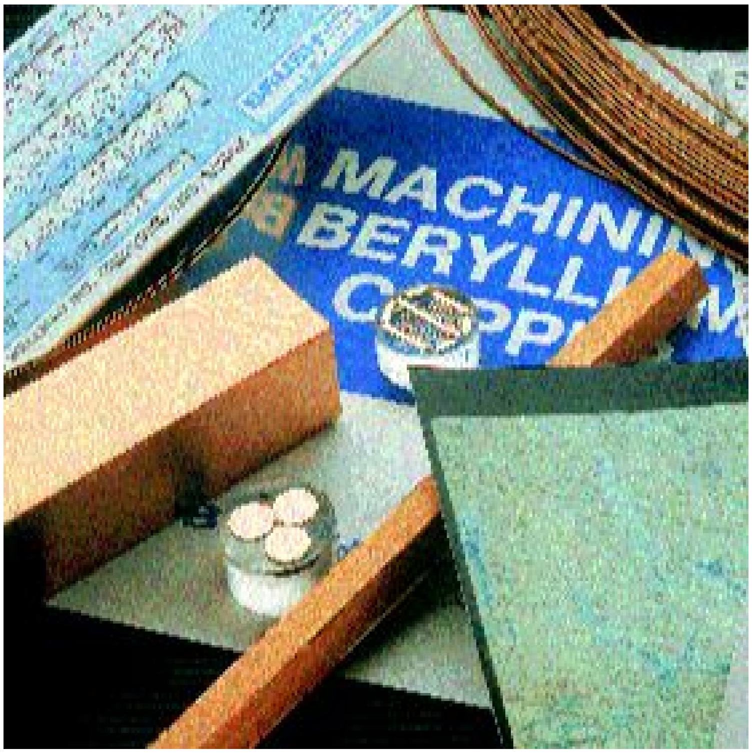
Section IV:
Material Properties

Section IV:
Material Properties
Mechanical

Design Guide -
Table of Contents

Fabrication / Size	Formability Machinability Solderability

Careful examination of the properties required for a particular design and the ranking of these properties in order of importance will assist the designer in selecting the material that has the required combination of properties.



Section IV: Material Properties Table of Contents Detail

The first subsection discusses the metallurgy of copper alloys that are relevant to their material properties; the remaining subsections discuss the mechanical and electrical / thermal properties of copper alloys.

Technical Exchange

Section III: Connector Requirements - Environment

Section IV: Design & Analysis - Metallurgy

Design Guide - Table of Contents

Technical Exchange

Section IV:
Material Properties
Electrical/Thermal

Section V:
Design & Analysis
Tolerance Analysis

Design Guide -
Table of Contents

List of Figures

Figure 26 Figure 28

Design Guide
Figure 27

FIGURE 25: TOLERANCE ANALYSIS

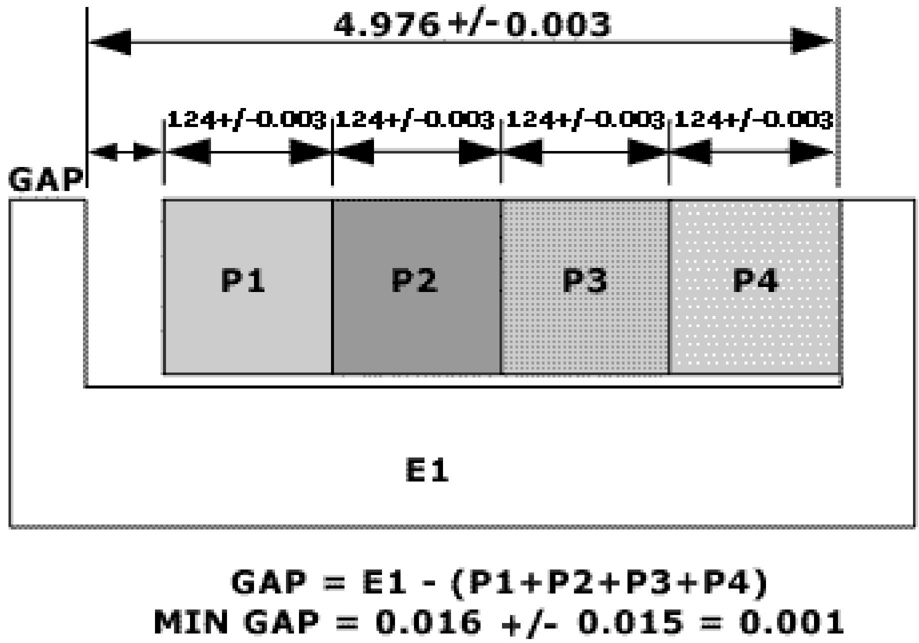


Figure 24b Figure 26

FIGURE 2: CONTACT GEOMETRY

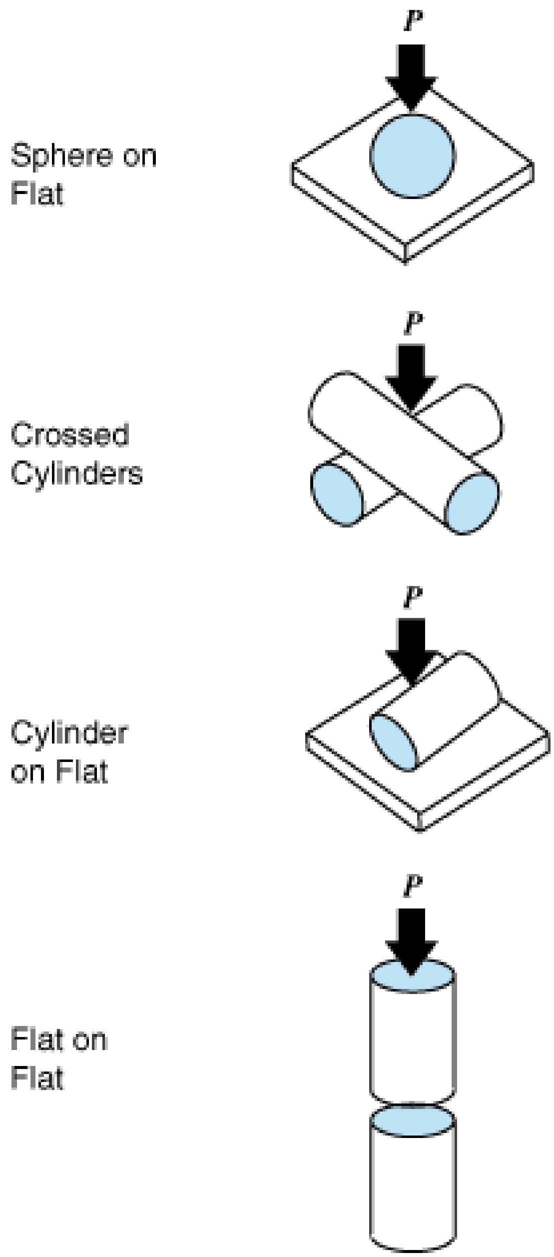


Figure 1 Figure 3

Figure 7 Figure 9

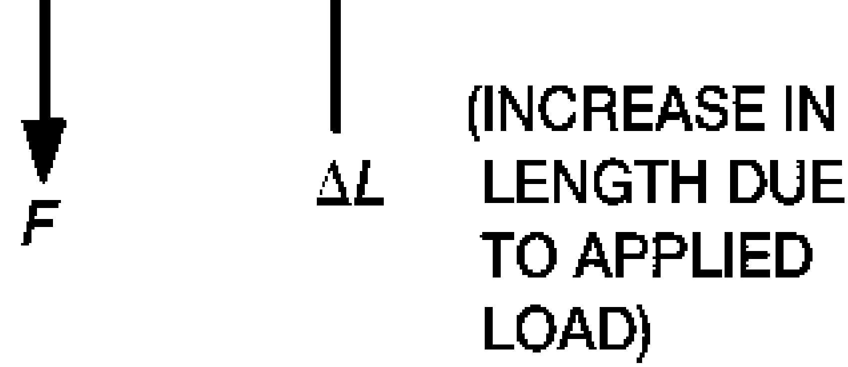


Figure 8 Figure 10

FIGURE 11: POISSON'S RATIO

Poisson's ratio $\nu = \dfrac{\Delta b / b}{\Delta l / l} = \dfrac{\text{lateral strain}}{\text{longitudinal strain}}$

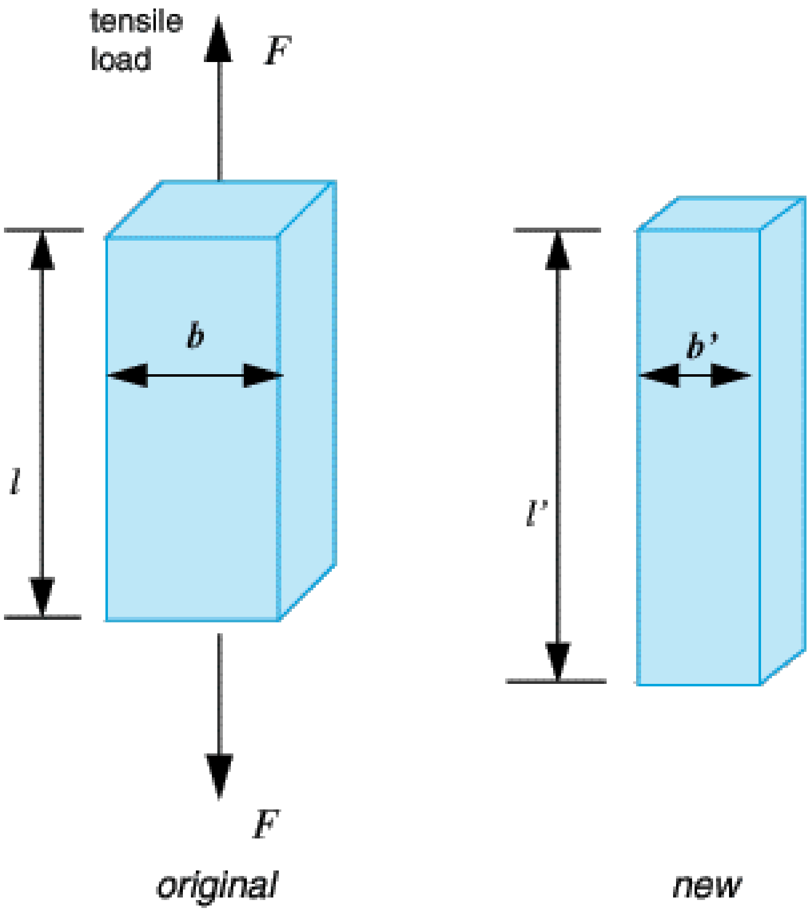


Figure 10 Figure 12

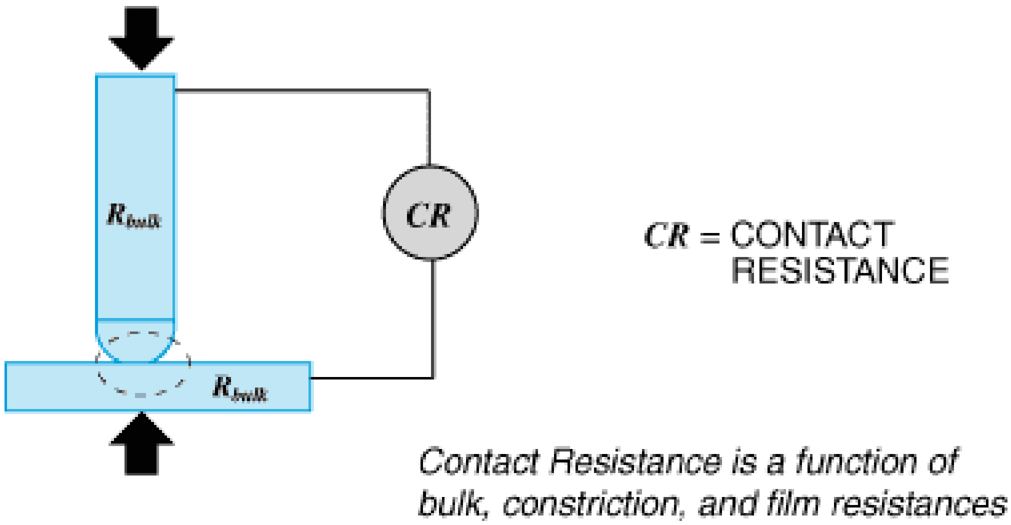
Technical Exchange

Section II:
Industry Trends

Section III:
Connector Requirements
Mechanical

Design Guide -
Table of Contents

FIGURE 3: CONTACT RESISTANCE



$$CR = \sum R_{bulk} + \frac{1}{\frac{1}{R_c} + \frac{1}{R_f} + \dots}$$

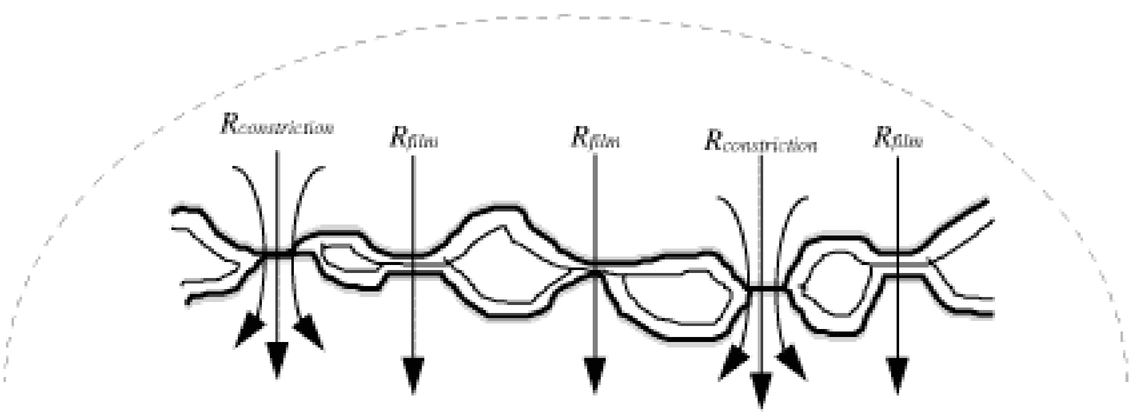
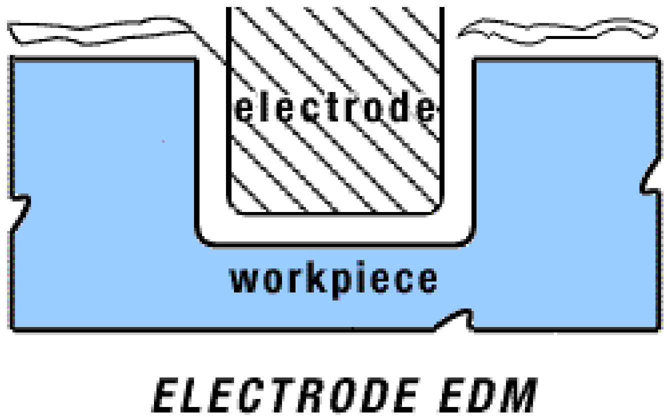
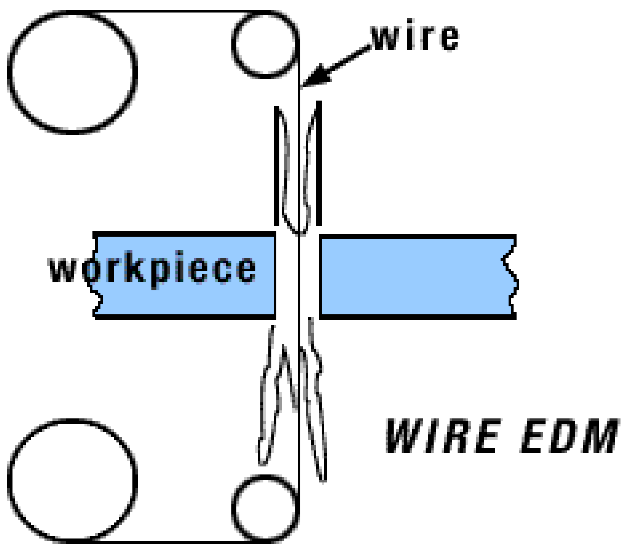


Figure 2 Figure 4

FIGURE 32:ELECTRICAL DISCHARGE MACHINING





List of Figures
Figure 31 Figure 33
Design Guide
Figure 32

Table 1 - Operating Environments

	T min		T max		Years of
Use Category	**(°F)**	**(°C)**	**(°F)**	**(°C)**	**Service**
Consumer	+32	0	140	+60	1-3
Computers	+59	+15	140	+60	≈5
Telecom	-40	-40	185	+85	7-20
Commercial Aircraft	-67	-55	203	+95	≈20
Industrial & Automotive Passenger Compartment	-67	-55	203	+95	≈10
Military Ground & Ship	-67	-55	203	+95	≈5
Space LEO & GEO	-40	-40	185	+85	5-20
Military Avionics	-67	-55	203	+95	≈10
Automotive Underhood	-67	-55	347	+175	≈10

Customer Technical Service

1- 800-375-4205
216-486-4200
E-mail: BrushWellman

North American Sales

Strip, Rod, Wire

Midwest	**East & West Coast**
Elmhurst, Illinois	Fairfield, New Jersey
Phone: 1-800-323-2438	Phone: 1-800-526-2538
Fax: 1-630-832-9657	Fax: 1-973-227-2649

Rod, Bar, Tube, Plate, Ingot

Warren, Michigan
Phone: 1-800-521-8800 or 1-586-772-2700
Fax: 1-586-772-2472

other services to support your design and production effort.
Please let us know of your need for any further information.

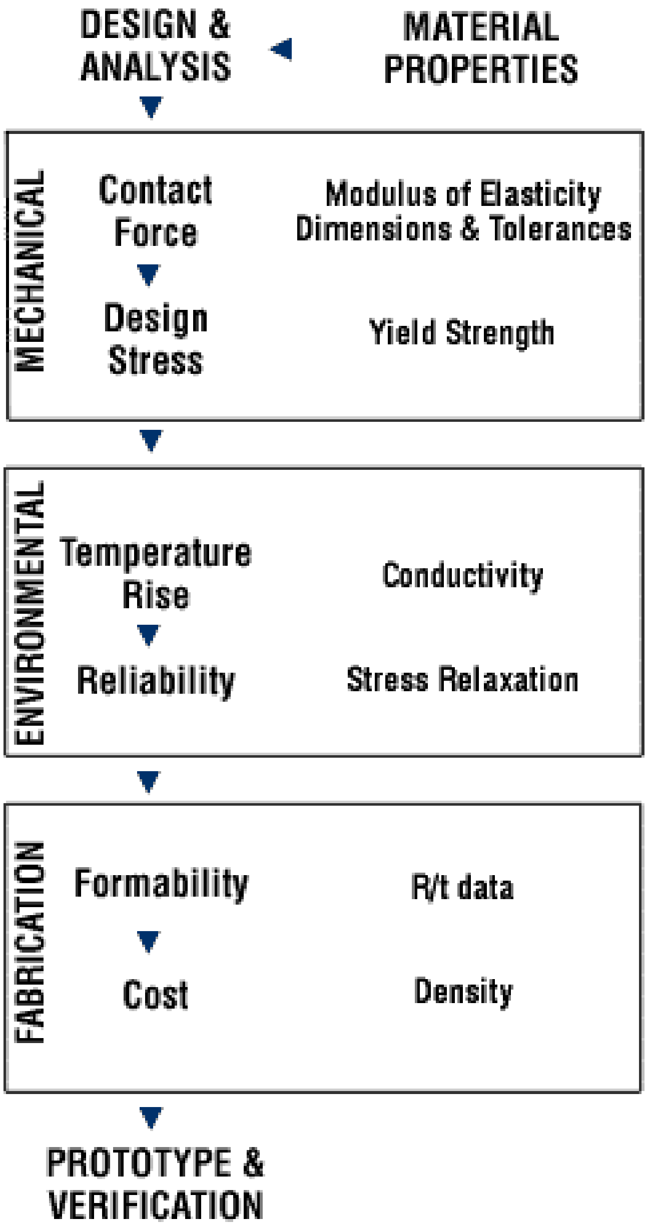
Technical Support -- technical service staff
Phone: **1-800-375-4205**
Email:

[List of Figures](#)

[Figure 44](#) [Figure 46](#)

[Design Guide](#)
[Figure 45](#)

Figure 3 Figure 5



Technical Exchange

Introduction

Section II: Industry Trends

Design Guide - Table of Contents
