Kirk-Othmer Encyclopedia of Chemical Technology.

ELECTRICAL CONNECTORS

Electrical connectors are mechanical devices that connect wires, cables, printed circuit boards, and electronic components to each other and to related equipment. Connector designs include miniature units for microelectronic applications; specialized cable; rack and panel designs for incorporating combinations of a-c, d-c, and radio-frequency conducting contacts; and high current connectors for industrial application and for transmission and distribution of electrical power in overhead and underground networks. Further categorization of connectors can be made according to: application, whether connectors permanently join conductors and components or permit separation and rejoining; the means used to effect connection, whether by fusion (welding, soldering) or by pressure, the values of which can be small or great enough to severely deform metal; the distribution type, whether of power or of low (signal) levels of current; and the conductor size. The term electrical contact describes the junction between two or more current-carrying members that provide electrical continuity at their interfaces. Connector contacts ordinarily remain stationary in active circuits, eg, they are not mated or separated. Components having electrical contacts other than connectors include circuit breakers, switches, relays, and contactors that are designed to interrupt or to establish current flow in active circuits, and slip rings and brushes that transmit current from a stationary to a moving frame of reference.

Many connectors for single conductors have an insulating sleeve, and almost all connectors that join two or more conductors have a plastic body, or dielectric, which separates the contact elements (see Insulation, electric). Metal or plastic shells with mechanical aids, such as screws, levers, and other coupling devices to facilitate joining and separation of the contacts, also may surround a connector. The shell may have mounting features for securing the connector to a chassis, supports for the wires and cables, and polarizing keys for prevention of improper mating.

1. Connector Configurations

1.1. Electronic Connectors

The complexity and size of many electronic systems necessitate construction from relatively small building blocks which are then assembled with connectors. An electronic connector is a separable electrical connector used in telecommunications apparatus, computers, and in signal transmission and current transmission ≤ 5 A. Separable connectors are favored over permanent or hard-wired connections because the former facilitate the manufacture of electronic systems; also, connectors permit assemblies to be easily demounted and reconnected when inspection, replacement, or addition of new parts is called for.

The emergence of integrated circuit technology, which was characterized by the development of direct linkage of many circuit components or linkage via conductive paths on tiny ceramic substrates, was thought to threaten the growth of the electronic connector market (see Integrated circuits). However, the explosive growth of electronics in most areas of manufacturing, business, and consumer products created new markets and resultant expansion of the connector field (see also Electronic materials; Electronics, coatings).

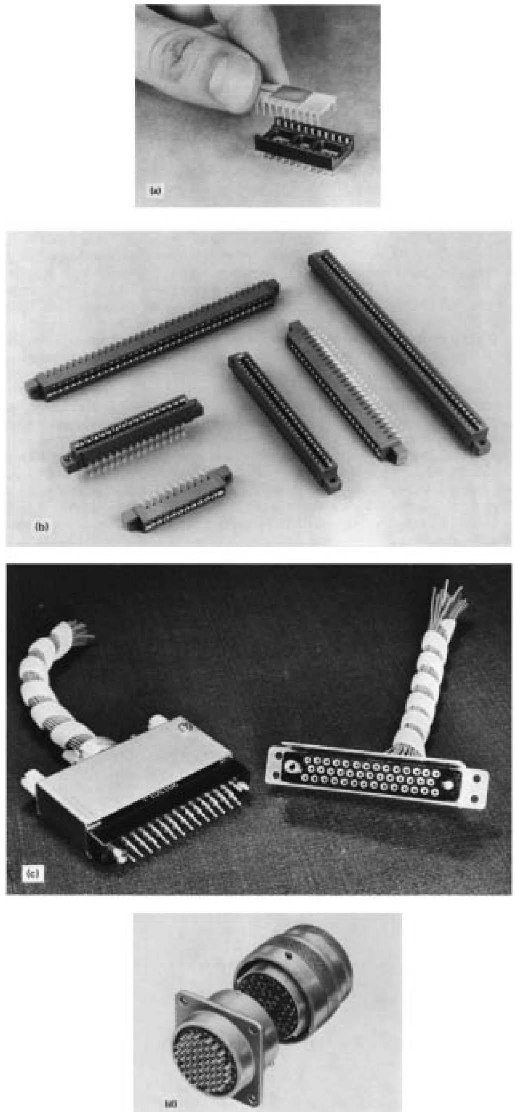

Fig. 1. Some types of electronic connectors. (**a**) Receptacle for dual-in-line package (DIP) semiconductor integrated circuit. (**b**) Connectors for printed circuit boards having edge contacts; two-piece connectors have male and female connector halves, one of which is attached to the printed circuit board, usually by soldering. (**c**) Rectangular connector for chassis mounting. (**d**) Circular connector for cable. (**a,d**) Courtesy of Burndy Corp.; (**b,c**)(courtesy of AMP Inc.)

Electronic connectors may connect internally or externally. Internal connections may be between a component and a printed circuit board or wire (Fig. 1**a**); a printed circuit board and a wire or another printed circuit board which is in a chassis (Fig. 1**b**); and between chassis in the same cabinet (Fig. 1**c**). External connectors join separate pieces of equipment (Fig. 1**d**).

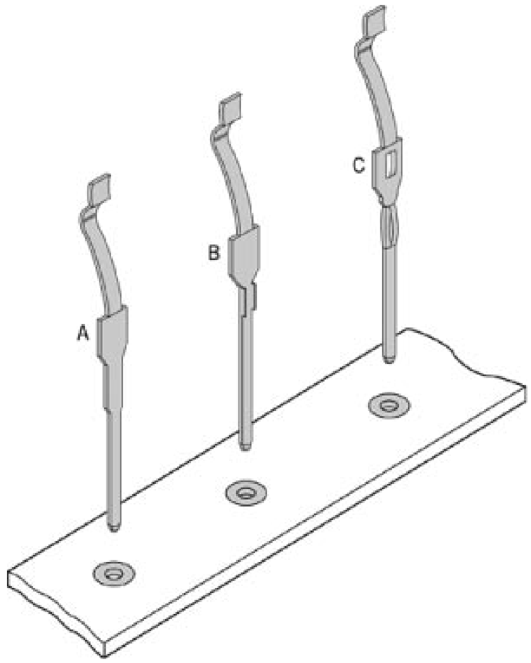

Fig. 2. Press-Fit pins of A, solid; B, crescent; or C, split-beam (compliant) design, are forced into through-holes of printed circuit boards where they interconnect conductors on opposite faces of the board.(Courtesy of AMP Inc.)

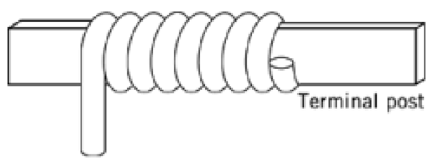

Fig. 3. Solderless wrap connection.

A popular connection system consists of square metal pins, usually 0.064 cm (0.025 in.) in size, that are pressed into holes drilled in a printed circuit board. The holes are copper (qv) plated on the insides and interconnect conductors on the top and bottom faces of the board. Multilayer boards have interior circuits that may also be interconnected in this way. The pins have either a solid shank or a deformable (compliant) cross section where the pins join the board (Fig. 2). Separable connectors or solderless wraps (Fig. 3) engage the ends of the pins. One end of the pin can be the contact and spring of a separable connector.

Surface mount refers to a method of securing connectors to the conductors of a printed circuit board by soldering appropriately shaped contacts to the board surface. Higher contact densities can be achieved and the need to drill holes in the board is avoided. Contact spacings may vary from about 0.5 cm for large current-carrying applications to 0.18 cm or less when miniaturization and high density is a requirement.

The contacts of an electronic connector have spring elements which press the mating surfaces together with a predetermined force, usually in the range of 0.25–5 N (0.056–1.12 lbf) for plated contacts; this range depends on the connector design and the materials from which the contact is made. Figure 4 illustrates typical spring designs. Mating of the connector is usually by sliding the surfaces together. Less frequently, the contacts are butted (Fig. 4**h**) after they have been positioned in zero insertion force (ZIF) connectors. Butting, which

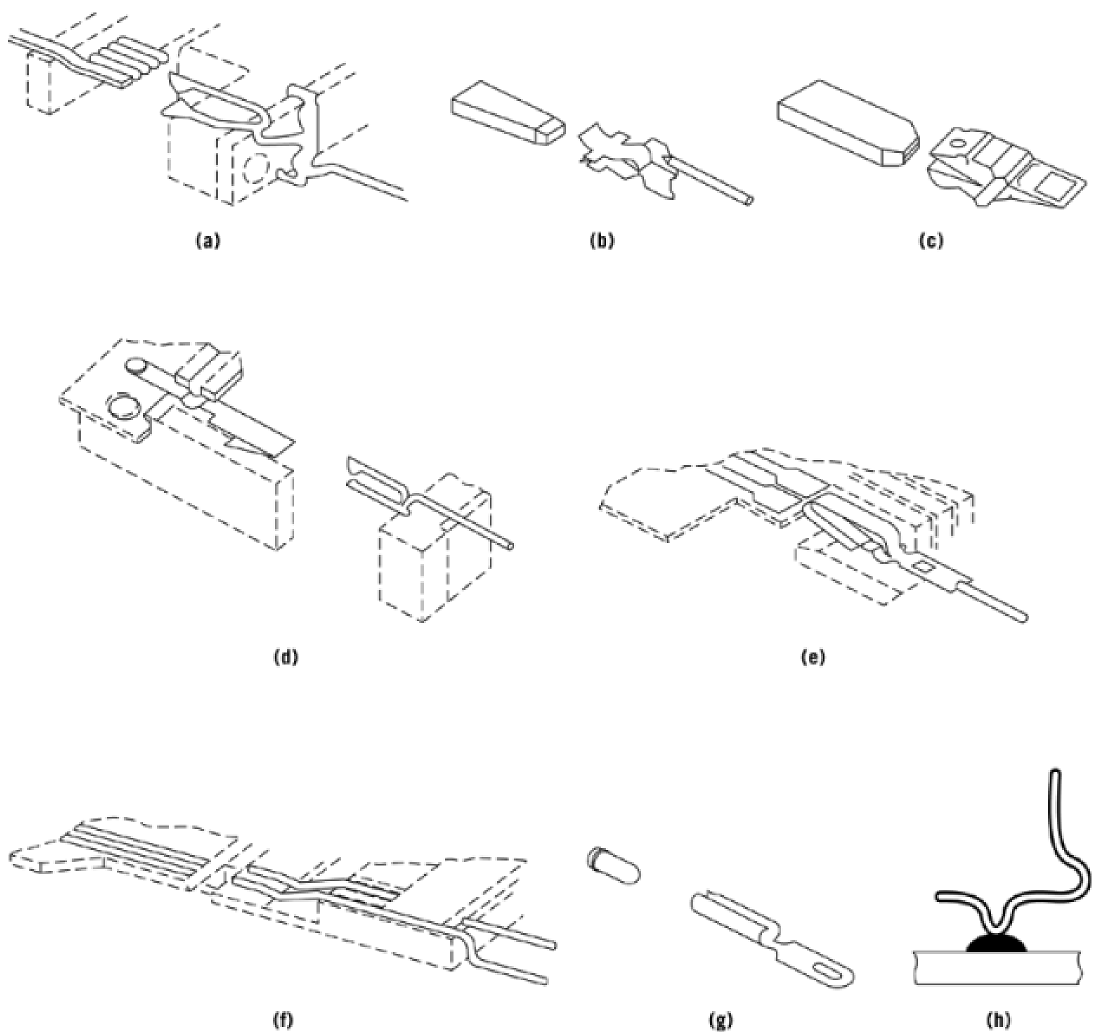

Fig. 4. Contact spring configurations for separable electronic connectors. Examples (**a**)–(**g**) are engaged by sliding the spring contact and its mating member together: (**a**)–(**d**) are blade-fork contacts; (**e**), folded cantilever contact for printed circuit boards; (**f**), straight cantilever contact for printed circuit boards; (**g**), pin-socket contact; and (**h**), butting contact. (**a**)–(**g**)(Courtesy of AT & T Bell Laboratories.)

requires separation of contact springs by means of a cam and lever or equivalent, is preferred to sliding the halves together as a method of mating connectors having more than 100 contacts because it requires smaller friction forces. Butting not only reduces mechanical wear, especially when soft metal finishes such as tin plate (1) are used as the contact material, but facilitates connection to the fragile legs of some components (Fig. 1**a**).

Another design which provides unusually low mating forces employs bundles of wires in both halves of the connector that intermesh, like two hair brushes, when the parts are connected (2).

1.1.1. Connector Shielding

Electromagnetic radiation, either human-made, ie, from tv, radios, radar, automotive ignitions, etc; or natural, ie, lightning, can interfere with the quality of signal transmission. Signals in conductors of electronic equipment

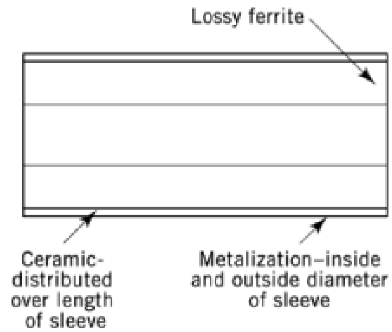

Fig. 5. Typical construction of a filter sleeve.(Courtesy of AMP Inc.)

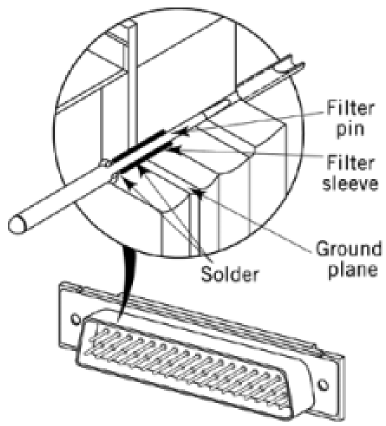

Fig. 6. Filter sleeve installed in a multicontact connector.(Courtesy of AMP Inc.)

including computers and communications gear may be seriously degraded. Methods used to control this effect include the use of coaxial cables and connectors in which shielding and grounding are used, twisted pair conductors, and filter connectors. An example (3) of this last is low pass filters for digital applications. These pass frequencies below a certain value and block any higher frequencies. One filter type consists of a special sleeve where the inside diameter is soldered to a center conductor such as a contact pin, whereas the outside diameter is soldered to a metal ground plane. Typical construction of the sleeve is given in Figure 5 and its use in a multicontact connector is shown in Figure 6.

Another type of electronic connector joins coaxial conductors. These have a solid or stranded center-conductor surrounded by a dielectric. The dielectric is covered with a conductive shield made of metal braid or tape and with a layer of insulation. Coaxial cable connectors terminate the center-conductor and the shield. These are used primarily in radio frequency circuits. The shape, dimensions, and materials of an electronic connector shell or structure may have to be designed to shield the connection from electromagnetic and radio frequency interferences in many applications.

1.1.2. Joining to Electronic Connectors

The most widely used techniques for the termination of wires to separate contacts are the soldering (see Solders and brazing alloys), welding (qv), crimping, solderless wrapping, and slotted-beam methods. Except for

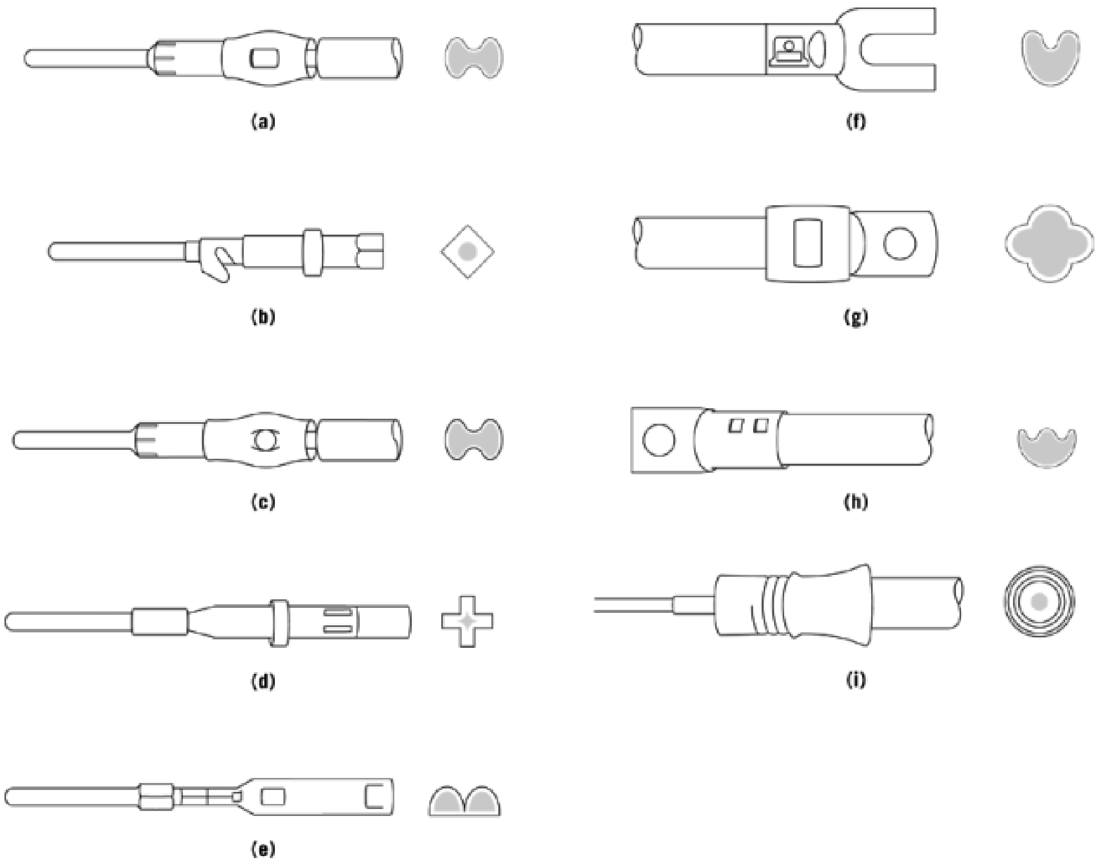

Fig. 7. Typical crimp contacts. Insets are cross sections of crimp indentations: (**a**) is longitudinal; (**b**), square; (**c**), double indent; (**d**), 4 indent; (**e**), B crimp; (**f**), nest indentor; (**g**) circumferential; (**h**), quad; and (**i**), interlocking.(Courtesy of Burndy Corp.)

crimping and welding, it is usually possible to replace wires to a contact a limited number of times if repair or wiring changes are necessary.

Soldering materials are alloys that are composed primarily of tin and lead (qv), and have low melting temperatures relative to the conductor metals which are being soldered (see Lead alloys; Tin and tin alloys). Welding requires sufficiently high temperatures for the fusion of metals.

Crimping is the compression of the back end of the separable contact, a tube, onto the wire conductor with a special tool that severely deforms both wire and barrel. This technique is suitable for joining both solid and stranded wires to connectors. Figure 7 illustrates typical crimp connections. Once the tool is removed the wire remains under the radial compression that is provided by the barrel. The force required to pull the copper wire from a crimped contact is approximately the same as its breaking strength. A soft metal, such as brass, is better for crimping than one having considerable springback, such as phosphor bronze (see Copper alloys).

In the solderless wrap (Fig. 3) or wire-wrap connection, a wire conductor is coiled around the back end of the separable contact, which has a square or rectangular cross section (4). The corners of the solderless wrap post and the areas of the wire that are in contact with it are severely deformed. In a properly made wrap, the force required to slide the wire along the post exceeds the breaking strength of the wire. The method is suitable only for solid wire, and special tools are used to make this connection.

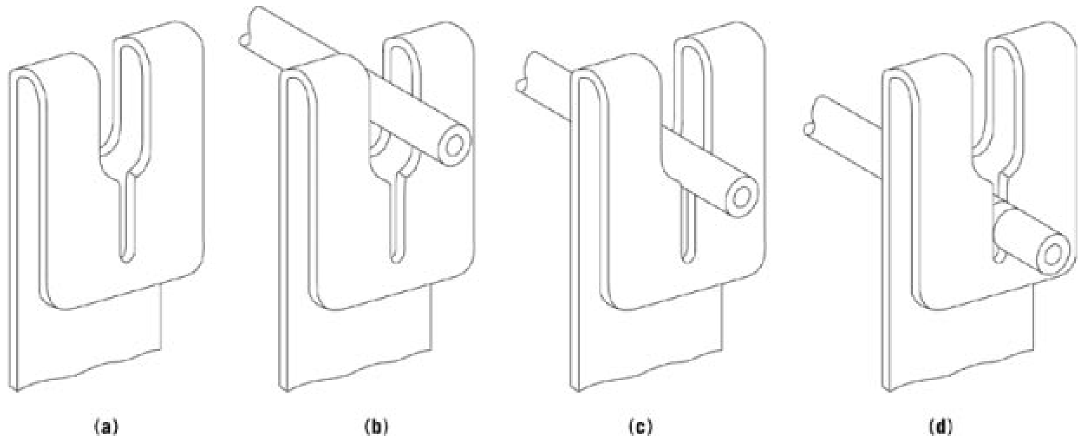

Fig. 8. Typical slotted beam connection where (**a**) is the terminal which resembles an inverted "U"; (**b**), the wire fits loosely into the upper portion of the slot; (**c**), the funnel shaped area displaces insulation; and (**d**), the conductor extrudes into the narrow bottom portion of the slot.(Courtesy of AMP Inc.)

Slotted beam or U-contacts describe a versatile design for the termination of solid wire and require that the wire be pushed into a narrow slot between two moderately rigid tines, or beams, at the back end of the separable contact (Fig. 8). The edges of the beams displace the insulation, squeeze the wire, and keep it in compression for the life of the connection. This termination method was developed for terminating conductors in a gang using flexible flat cables with round conductors (5).

Methods used to secure a wire to the back end of a separable contact include the taper pin and the solderless clip. The former is a cylindrical tapered body having a hollow end into which a wire is crimped; the front of the taper pin is forced into the back end of the connector contact which has conforming shape. The solderless clip has a spring which traps the solid or stranded wire against a post at the back end of the separable contact; the clip encircles both the wire and the post (6).

1.2. Splicing Connectors

Splicing connectors are used to permanently join wire to wire. Some are simple sleeve barrels that are crimped to bare wire; others are preinsulated where the crimp is made by compressing the sleeve and its positioned insulation onto wires which may or may not have insulation. Two types of splicing connectors, which require insulation displacement and are used in the telecommunications industry, are illustrated in Figures 9 and 10. The connector in Figure 9 has a spring-tempered phosphor bronze liner that pierces the insulation and contacts the wire and an outer shell of soft brass (7). This connector is suitable for paper-insulated solid conductors. The slotted-beam connection principle is exemplified in the connector shown in Figure 10. This connector gang-terminated 25 pairs of wires using either paper or plastic insulation (8). The conductor can be aluminum or copper and its diameter ranges from 0.40–0.81 mm (20–26 American Wire Gage). A grease sealant is used to provide moisture resistance.

1.3. Terminals

Terminals are connectors having individual wires that are designed to be screwed down at separable ends, and to which conductors are permanently joined at the back end, usually by crimping. Figure 11**a,b,c** illustrates common terminal configurations. Either ring or open-tongue configurations provide a terminal for the screw

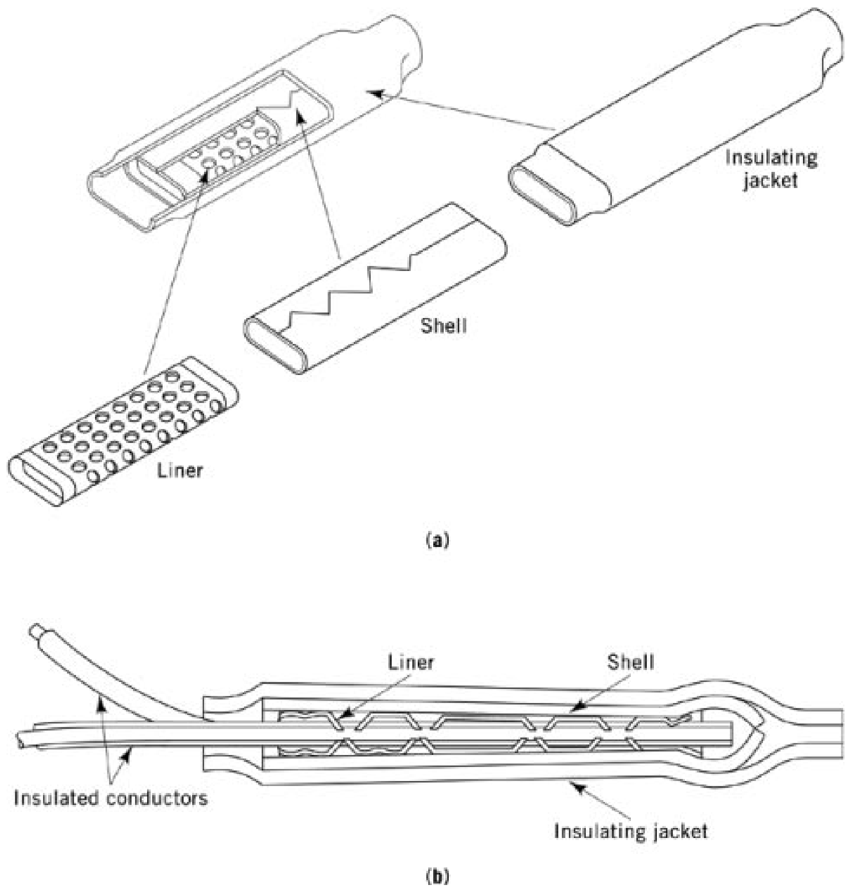

Fig. 9. Splicing connector for two wires (insulation piercing). (**a**) Exploded view; (**b**) cross section after pressing on wires.(Courtesy of AT & T Bell Laboratories.)

connection. Another popular terminal, called a quick disconnect (Fig. 11**d**), has a spring receptacle into which a contact tab with a rectangular cross section is inserted. This latter design is widely used in the appliance industry.

1.4. Utility and Industrial Connectors

Connectors used in power distribution systems are nearly always of the permanent type and are usually made for single conductors. Sleeve barrels are used to splice cable by crimping (Fig. 12**a**). Insulating covers may be applied to the connector after the joint is made between the connector and the insulated cable. Clamp-type connectors are used with one or more clamping bolts and may have additional resilience when used with dished washers made of spring steel (Belleville washers). Figure 12**b** illustrates a typical clamp connector in a terminal configuration which is used for insulated conductors in building construction applications. Most crimp power connectors for aluminum and copper cable are made of aluminum. Those that are fabricated from copper alloys are for copper cable only. Clamp connectors are made of copper and aluminum alloys.

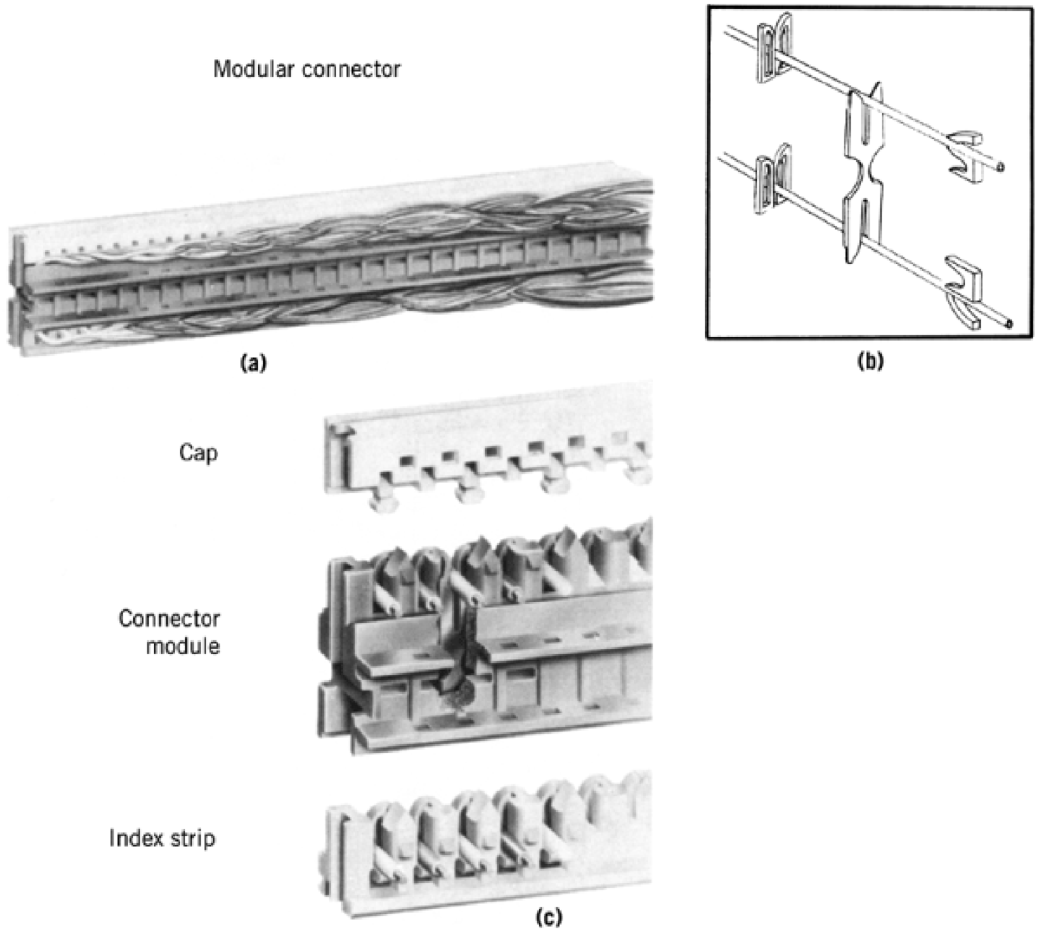

Fig. 10. (**a**) Splicing connector for terminating 25 pairs of telephone wire; (**b**) schematic of the slotted-beam insulation piercing contact; and (**c**), components of the modular connector.(Courtesy of AT & T Bell Laboratories.)

1.5. Methods of Application

Attachment of separable contacts to conductors may be achieved using automated machinery or specialized hand tools. The automated machinery method is popular in large-volume original equipment markets for products such as strip terminals, rack and panel connectors, and printed circuit-board connectors. This machinery applies contact components to conductors, but the insertion of the conductors and the applied contacts into connector housings is usually performed manually. The cases in which the desired connection is not amenable to automation require the use of hand-tooled application. Products included in this category are heavy-duty terminals and splices, connectors to which conductors are terminated by soldering, and small wire terminals. Hand-tool application is typically associated with utility, construction, maintenance and repair, and small-volume original equipment markets. The largest connectors, which are employed by utilities for construction and servicing of power distribution lines, require installation tools powered by hydraulic means, compressed air, or small explosive charges.

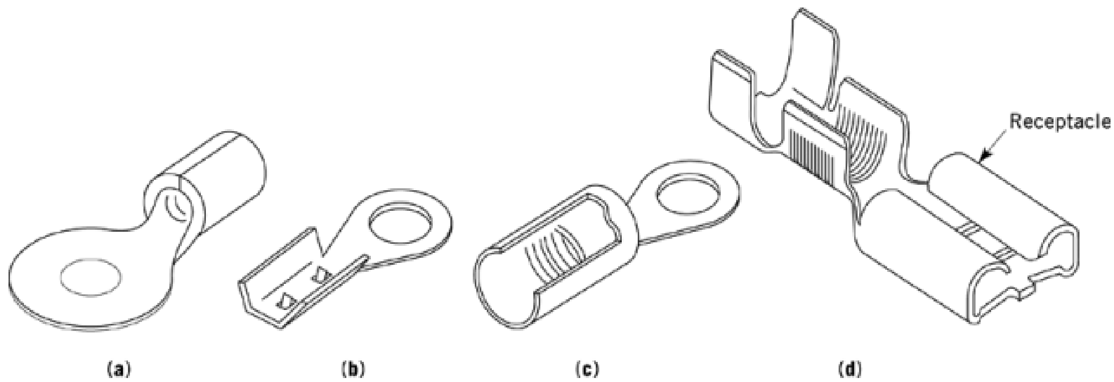

Fig. 11. Crimp terminal configurations: (**a**) straight barrel, 90° tongue, where wire without insulation is crimped in the barrel. (**b**) Open barrel having insulation-piercing lances. (**c**) Nylon or poly(vinyl chloride) preinsulated terminal accommodating and supporting wire insulation. Wire without end insulation is inserted in the terminal and is crimped. The terminal sleeve is not broken but conforms to the shape of the crimp indent. (**d**) Quick disconnect terminal having a crimp barrel and provision for insulation support.(Courtesy of AMP Inc.)

2. Contact Principles

The design of electrical contacts and the selection of contact materials are based on a body of interrelated physical, metallurgical, and chemical principles. In the early 1920s, Ragnar Holm pioneered studies on the origin of resistance to current flow at the surfaces of touching metallic bodies. From those investigations contact science emerged as a specialized field of physics and materials technology.

2.1. Nature of Mechanical Contact

The surfaces of solids are irregular on a microscopic scale. Even nominally plane, smooth surfaces have a large-scale waviness on which is superimposed a roughness having peak-to-valley distances of several micrometers. When two metallic bodies are placed in contact at a light load, the bodies touch at only a few small spots, or asperities. As the load is increased, more and more asperities come into contact and the surfaces move together. The true area of contact depends, therefore, on normal load and on the hardness of the metal. The real area of contact is only a fraction of the apparent area in most cases, except at very high loads. For example, the ratio of real to apparent contact areas of finely lapped steel flats having an apparent area of one cm^2 is ca 10^{-4} at a force of 10 N (2.25 lbf).

2.2. Nature of Electrical Contact

If metallic surfaces are covered by a nonconducting layer, such as an oxide or a sulfide tarnish film, the area of metallic contact is zero provided that the film is unbroken. Significant current does not flow between such surfaces except when the film is less than 2–3 nm in thickness. At or less than these thicknesses, electron tunneling (tunnel conduction), which is voltage independent, occurs by a wave-mechanical effect analogous to the transmission of light through metal foil of thickness comparable to the wave length (9). If the nonconductive layer on a surface is discontinuous or is punctured, the mechanical load is borne by both film and metal. Current then flows through the metallic spots, called a spots (10). The lines of electric flow converge at these spots, as illustrated schematically in Figure 13. Constriction resistance, the increase of resistance beyond that of a continuous solid, ie, not having an interface (11), originates at this convergence.

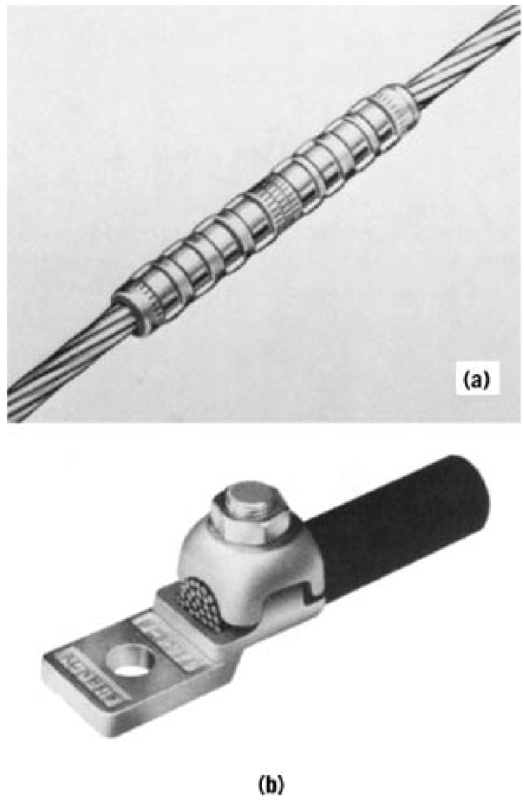

Fig. 12. Typical connectors for power distribution cable. (**a**) Aluminum sleeve barrel for uninsulated cable. (**b**) Clamp-type terminal connector for insulated cable used in a building construction.(Courtesy of Burndy Corp.)

In the simplest case, for a single circular contact spot between identical metals having a uniform film, contact resistance R has the relationship:

$$R = R_c + R_f$$

$$R = \frac{\rho}{2a} + \frac{\sigma}{\pi a^2}$$

where R_c = constriction resistance, R_f = film resistance, a = radius of the a spot, ρ = bulk resistivity of the contact metal, and σ = film resistance (ohms per unit area). The radius of the a spot can be calculated from the hardness of the metal and the applied load.

Because a length of metal associated with the connector contact is ordinarily in the path between the contact end to which a wire is terminated and the contact interface, its resistance (bulk resistance) must be added to contact resistance when considering the connector as a circuit element. This overall resistance is sometimes erroneously called contact resistance.

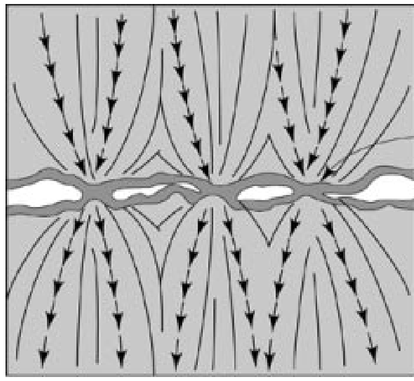

Fig. 13. Schematic of a microscopic view of contact interface where constriction resistance originates in the constriction of current flow through the touching metallic junctions (a spots) of the mating surfaces. The arrows and lines indicate the flow of current.

Table 1. Softening and Melting Voltages[a]

	Softening		Melting	
Metal	°C	V	°C	V
Sn	100	0.07	232	0.13
Au	100	0.08	1063	0.43
Ag	150–200	0.09	968	0.37
Al	150	0.1	660	0.3
Cu	190	0.12	1083	0.43
Ni	520	0.22	1453	0.53
W	1000	0.6	3380	0.1

[a]Ref. 12.

2.3. Resistance Heating of Contacts

The contact material, contact area, and heat dissipating ability, as well as the heat dissipating ability of the structure to which the material is attached, limit the amount of current that a contact can transport. Excessive current heats and softens the metal contact. This softening results in an increase in the surface area of the contact and a corresponding reduction in contact resistance.

At higher currents, the mating junction melts. Both softening and melting occur at characteristic voltages. Typical values are shown in Table 1.

2.4. Voltage Breakdown of Films

If a significant voltage can be passed by a circuit across a film-covered contact, the film, depending on thickness and composition, may break down electrically. This action, called the coherer effect or fritting (13), results in the formation of minute metallic conductive paths through the film. Puncturing is of the order of 0.1 V/nm of film. The potential drop across the film after puncturing is the melting point voltage.

2.5. Overview

Metallic contact between surfaces of separable connectors usually is obtained either by using noble metals, which are essentially film-free, or by designing the contact so that any films that are present are broken before or as the surfaces are brought together. For example, noble metal coatings on base metal substrates having high conductivity, such as copper alloys, are used for small multicontact connectors which can provide small mechanical loads normal to the surface. Alternatively, soft metal contacts of, for example, tin and tin–lead alloy platings can be used because films on their surfaces are easily disrupted on closure. In the latter case, mechanical wear from sliding connector designs may severely limit the numbers of insertions and withdrawals that are possible. In the case of power connectors, severe deformation of the aluminum or copper surface is obtained by crimping or clamping facilitating disruption of the oxides on both the connector and conductor surfaces. Tin plate is used widely on aluminum connectors, and wire brushing of the cable (especially if it is made of aluminum) and joint aids increase the areas of metallic contact and thereby lower contact resistance. A large part of practical connector engineering is devoted to designing metallic contacts that need minimal maintenance, especially for those intended to serve in chemically aggressive atmospheres and in high temperature applications.

The contact resistance of any electrical connector in a circuit must be stable and generally low for proper functioning of that circuit. Low voltage circuits, which are common in modern electronic systems, have open-circuit voltages of not more than a few volts. These are insufficient levels for the fritting of films that grow on base metals from environmental exposure. Metallic bridges established by fritting are fragile, and the voltage drop across fritted surfaces may permit heating and consequent degradation of the contact. It is, therefore, generally undesirable to rely on fritting as a method that may establish current flow in a connector. Low contact resistance should be achieved using noble metal contacts or base metals concurrently with methods that mechanically perforate any insulating films that are present.

Typical separable electronic connectors have contact resistances that range from several milliohms to tenths of ohms. Utility–industrial connectors, which are established by very high pressure connection and are exemplified by a bolted joint, have contact resistances of microohms. Crimping, solderless wrapping, and other methods used to establish connection of wires and other conductors to electronic connectors have associated contact resistances of ca 10–100 $\mu\Omega$. The bulk resistance of the conducting elements, which include connector parts such as the spring, barrel, and pin, is usually several times greater than the contact resistances of the separable contact interface and the terminal ends. The overall resistance of electronic connectors generally ranges from 3–30 mΩ.

3. Materials and Processing

3.1. Contact Substrates

The substrate must be able to be terminated readily as well as be a good electrical conductor. In electronic connectors the substrate may serve as a spring element. The most widely used spring materials for connectors are the copper alloys: 98.1 wt % Cu; 1.9 wt % Be (Unified Numbering System (UNS) designation C17200); 94.8 wt % Cu, 5.0 wt Sn, 0.19 wt % P (phosphor bronze, C51000); and 88.2 wt % Cu, 9.5 wt % Ni, 2.3 wt % Sn (C72500) (see Copper alloys). Sometimes springs made of metals that have poor conductivity, such as stainless steel, are used as inserts in connector barrels of brass or similar metals which are inexpensive and can be terminated easily.

The contact ends of printed circuit boards are copper. Alloys of nickel and iron are used as substrates in hermetic connectors in which glass (qv) is the dielectric material. Terminals are fabricated from brass or copper; from nickel, for high temperature applications; from aluminum, when aluminum conductors are used; and from steel when high strength is required. Because steel has poor corrosion resistance, it is always plated using a protective metal, such as tin (see Tin and tin alloys). Other substrates can be unplated when high contact normal forces, usually more than 5 N, are available to mechanically disrupt insulating oxide films on the surfaces and thereby assure metallic contact (see Corrosion and corrosion control).

3.2. Contact Finishes

Base metal substrates quickly develop oxides, tarnish, or corrosion films, in humid, polluted atmospheres. Because these films may prevent adequate metal-to-metal contact when the connector or connector–conductor surfaces are mated, coatings of other metals commonly are used to obtain corrosion resistance, to provide conductivity, or to facilitate termination to conductors by soldering, wire wrapping, or by other means. Application of finishes is achieved by electroplating (qv), cladding, and by hot-dipping when low melting metals such as tin are used (see Metal surface treatments). Selective application of a contact finish to portions of the substrate can be accomplished using any of these coating techniques. The principal noble contact finishes are gold, palladium, rhodium, and alloys having a high gold or palladium content. Palladium-based finishes usually have a thin (0.05–0.1 μm) top coating of gold. The non-noble finishes are tin, silver, and nickel. Alloys of these metals, such as 50 wt % Sn, 50 wt % Pb, also are widely used.

3.2.1. Noble Metal Electroplated

Because it is chemically stable, gold is the noble metal most extensively used in the contacts in electronic connectors; metric ton quantities are consumed annually for this purpose. The high cost of noble metals requires that these materials be sparingly, however effectively, used. The chief requirement of a plated finish is sufficient thickness. Gold coatings in thicknesses of 0.1–2 μm are used; the greater thicknesses are required for critical applications and for wear resistance when large numbers of engagements of the connector are specified. Rhodium ordinarily is plated from only 0.5–1 μm. Thicker coatings have a tendency to crack spontaneously. The thickness of palladium and palladium–nickel (commonly the 80 wt % Pd, 20 wt % Ni alloy) electrodeposits parallels that of gold.

Porosity ranks next to thickness in importance, especially when the finishes must serve in polluted and/or humid environments which promote tarnish and corrosion. Pores, openings in the surface that extend to the underplate or substrate, can be intrinsic in the coating (14), or can be produced by mechanical wear or by forming operations involved in manufacturing. In some environments the substrate can tarnish or corrode at pore sites and can produce localized areas of insulating films which cause contact resistance to increase. Porosity is less important for connectors that operate indoors at moderate to low relative humidities and in the absence of corrosive pollutants (15).

Hard deposits enhance a contact's resistance to mechanical wear. Palladium, palladium–nickel alloy, and gold electrodeposits containing 0.1–0.5 wt % cobalt or nickel are more wear resistant than pure gold finishes (16). Deposits must be solderable if the associated terminations are to be soldered. Gold deposits thicker than 2.5 μm form brittle gold–tin intermetallics (17) during soldering and, therefore, give weak joints. Contaminated surfaces are also difficult to solder.

Underplatings normally are used for noble metal electrodeposits. Zinc from brass rapidly diffuses through gold plate and forms insulating films on the plated surface. Its rate of diffusion is reduced by copper or nickel underplatings (18). Diffusion of copper through gold plate, especially at temperatures above 100°C, can be troublesome, and nickel underplate is used to retard the diffusion rate (18). Copper and nickel underplatings are usually used to lower porosity in a noble metal deposit (14). The effective hardness of a multilayer coating is increased by hard underplates. The wear resistance of gold deposits can be improved by nickel underplating (19). Pure electroplated nickel is ductile and harder than most substrate metals, and the thickness of the nickel underplate should be at least 1.25 μm in order to significantly reduce wear. The corrosion tendency of contacts that have porous noble metal finishes is lowered by nonreactive underplatings, such as 65 wt % Sn, 35 wt % Ni (20).

3.2.2. Clad Inlay Noble Contact Materials

Insertion of a strip of metal into a groove in a base metal substrate which is then metallurgically bonded to the substrate by rolling at high pressures (Fig. 14) is referred to as cladding (21). The metals must be ductile, and

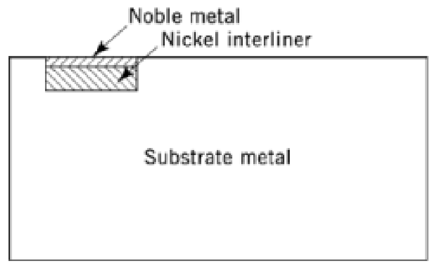

Fig. 14. Schematic of a clad inlay contact material.

some copper alloys, such as C72500 and C15000, which are used in connector springs, are especially suitable for this purpose. Pure gold, pure palladium, and alloys of gold and silver or nickel, such as 75 wt % Au, 25 wt % Ag; 96 wt % Au, 4 wt % Ni; and 60 wt % Pd, 40 wt % Ag having a thin gold cap which has been partially diffused into the palladium alloy by heating (22), are widely used clad inlays for electronic connector contacts. Because intermediate heat treatments as well as several passes through the rolls are usually necessary in order to achieve the desired thickness reduction, a nickel interliner is ordinarily used as a diffusion barrier. The same thickness and porosity requirements for electrodeposits apply to clad noble metal finishes.

Cladding may be less expensive than selective electrodeposition when coatings greater than 1 μm of a noble metal are required, but may be more expensive than electrodeposition for thinner coatings. Selective techniques are most easily used for sheet metal substrates that are to be machine stamped and formed into contacts. Clad noble metals are considerably more ductile (and less hard) than comparable electrodeposits and, therefore, are better suited to forming operations. Contacts that are made into separate parts from rod by screw machining are usually coated on all exposed surfaces by barrel electroplating.

3.2.3. Noble Metal Weldments

Noble metal contact buttons, 25–75 μm thick, are made by resistance welding a rod of the material to the substrate, which usually is a contact spring, and by cutting the rod and forming the button to the desired shape. Pure gold and gold–silver alloys are the most commonly used metals.

3.2.4. Base Metal Finishes

The low cost of base metal finishes obviates selective coating. Electrodeposition is used for 0.5–5 μm thick coatings of tin and tin–lead alloy, usually about 50 wt % Sn, 50 wt % Pb, on electronic connector contacts, on contacts at the edges of printed circuit boards, and on terminals. Sheet copper alloys that have been coated with tin–lead alloy are widely used for contacts that are stamped and then formed into the desired shapes, such as pins having a closed end and sockets. Aluminum connectors that have utility–industrial applications are more thickly coated, and hot-dipping in molten tin is common.

Whiskers are filamentary growths a few micrometers in diameter that occur spontaneously from tin and other low melting pure metals in response to lattice strains. Whiskers can attain lengths of several millimeters and may short-circuit adjacent contacts. The presence of whiskers is unimportant if currents are in the ampere range, because bridging is instantly cleared by melting. Whisker formation can be retarded by combining small amounts of alloying elements, such as lead or copper, with tin coatings or by fusing the coatings after plating (23).

3.3. Conductive Elastomers

Conductive elastomers (qv) (24), rubbers that are made conductive by molding metal or carbon powders in them, have characteristics of both a contact material and a spring. Silicone rubbers, neoprene, polyurethane, and other elastomers have been used; however, silicones are the most popular because these have a low compressive set and operate over a wide temperature range, from ca -65 to 200°C (see also Antistatic agents; Electrically conductive polymers). Particle loadings are high, eg, 70 wt % or more for metals, because there must be particle contact through the body for the elastomer to be conductive. Silver is used in those contacts that must be highly conductive and other metals are used in systems where higher resistance can be tolerated.

However, conductive elastomers have only ca $\leq 10^{-3}$ of the conductivity of solid metals. Also, the contact resistance of elastomers changes with time when they are compressed. Therefore, elastomers are not used where significant currents must be carried or when low or stable resistance is required. Typical applications, which require a high density of contacts and easy disassembly for servicing, include connection between liquid crystal display panels (see Liquid crystals) and between printed circuit boards in watches. Another type of elastomeric contact has a nonconducting silicone rubber core around which is wrapped metalized contacts that are separated from each other by insulating areas (25). A newer material has closely spaced strings of small spherical metal particles in contact, or fine solid wires, which are oriented in the elastomer so that electrical conduction occurs only in the Z direction (26).

3.4. Contact Lubricants

Debilitating wear of separable connector contacts, which may occur if the metallic coating is thin or if forces normal to the contact surfaces are high, can be minimized by coating the contacts with thin films (qv) or organic lubricants (16, 27) (see Lubrication and lubricants). Viscous mineral oils, poly(phenyl ethers), per(fluoroalkyl) polyethers, soft microcrystalline waxes (qv), and petrolatum have been used on electronic connector contacts. Although these lubricants are insulators, the few asperities of the metal pieces that make contact through the film provide low contact resistance, which is indistinguishable from that of unlubricated contacts. Some lubricants have corrosion inhibiting or antitarnishing properties for base metals and for porous noble metal finishes (16).

3.5. Joint Aids

Good metallic contact with aluminum connectors or aluminum conductors, including those with severely deformed surfaces, is difficult if aluminum oxide is present. It is believed that contact occurs by extrusion of the substrate metal during deformation through minute cracks produced in the oxide; and that some degree of geometric matching of cracks is necessary (28) when both of the surfaces are aluminum. It has been found that finely divided zinc incorporated in grease can be coated on the interior surfaces of an aluminum connector to provide lower initial contact resistance and better long-term resistance stability (29). The grease is also able to retard ingress of air and water which can seriously degrade reliability of aluminum connectors, especially in exposed out-of-doors service in power distribution networks. Other soft metal coatings are effective, such as indium, which has been proposed (30) as a plating on copper alloy connectors intended for permanent joints to aluminum communications cables having slotted-beam connectors.

3.6. Insulators

Molded plastics serve as insulators for multicontact connectors and glass is used in hermetic connectors intended for bulkhead mounting. Environmentally sealed circular connectors combine both elastomeric technology with plastics by bonding the seals and grommets to the plastic insert. A wide variety of plastics are employed in electronic connector bodies depending on the size, strength requirements, complexity of the design, and service environment. Plastic materials are often reinforced using about 30 to 40% glass fibers. Thermoplastics are favored by a wide margin over thermosets for electronic connectors because of manufacturing economies and generally superior performance.

Automated soldering operations can subject the molding to considerable heating, and adequate heat deflection characteristics are an important property of the plastics that are used. Flame retardants (qv) also are often incorporated as additives. When service is to be in a humid environment, it is important that plastics having low moisture absorbance be used. Molding precision and dimensional stability, which requires low linear coefficients of thermal expansion and high modulus values, are key parameters in high density fine-pitch interconnect devices.

Nylon and poly(vinyl chloride) sleevings are used for preinsulated terminals. Ceramics (qv) are employed in some high voltage power connectors. Hard rubber shells insulate connectors that serve underground power distribution cables.

Some of the common types of plastics that are used are thermoplastics, such as poly(phenylene sulfide) (PPS) (see Polymers containing sulfur), nylons, liquid crystal polymer (LCP), the polyesters (qv) such as polyesters that are 30% glass-fiber reinforced, and poly(ethylene terephthalate) (PET), and polyetherimide (PEI); and thermosets such as diallyl phthalate and phenolic resins (qv). Because of the wide variety of manufacturing processes and usage requirements, these materials are available in several variations which have a range of physical properties.

4. Reliability and Testing

Connectors must be as reliable as any component in the circuits that they serve. Reliability requirements of each connection are particularly stringent in complex apparatus or where signal and power must be carried long distances along a series of connector contacts. The consequences of failure include not only loss of service, but the great expense of locating the failure, exposing the connection, and making a replacement.

Considerable effort has been directed to determining the causes of connection failures and to learning how to minimize the likelihood of occurrence. Acceptable failure rates range from <1 in 10^9 operating hours for contacts in air-frame (31) electrical systems and in some telecommunications equipment, to 100–1000 in 10^9 operating hours in instruments, to even larger rates for contacts in many consumer products. A failure is defined as exceedance of contact resistance, which can be as little as twice the initial contact resistance, that causes circuit malfunction. The required lifetimes of connectors may be $\geq$20 yr, although most required application times are shorter (see Materials reliability).

4.1. Mechanisms of Failure

The causes of connector contact failure can be of a thermal, chemical, or mechanical nature, in addition to misapplication and physical abuse.

4.1.1. Thermal

If a connector is in an environment hotter than that for which it was designed, or if it undergoes significant resistive heating resulting from excessive current flow, the following can occur and eventually may cause failure: (*1*) stress relaxation of the contact spring, or creep of the deformed metal, as with crimp barrels, which are responsible for maintaining pressure contact; (*2*) acceleration of chemical reactions that cause failure; for example, rapid thickening of the oxide on base contact surfaces may occur even when they are mated if the contact is not gas tight, eg, if the contact is unable to resist encroachment of the atmosphere at the mating site; (*3*) accelerated diffusion of substrate metals or of base hardener and impurity metals through the surface of noble metal platings and the formation of insulating films; and (*4*) volatilization of connector contact lubricants.

Alternating temperature cycles may be more damaging than a constant elevated temperature because differences in the amount of expansion and contraction of the members supporting the contacts can cause breakage of the metallic junctions (a spots). When there is an insulating film on the surface between the a spots as with base metals, metallic contact cannot be maintained owing to the movements. Heat cycling forms the basis of much connector testing, eg, 500 cycles of heating by current flow to 100°C above ambient followed by cooling to room temperature for aluminum conductor overhead power distribution connectors (29). A connector is acceptable if this stress does not cause significant change in overall resistance.

It is not practical to determine the contact resistance in power connectors. The resistance of the connection of a specified length of conductor on each side of the connector is measured and is called the overall resistance or the connection resistance. One industry specification (32) defines the included lengths and requires the stability of the connection resistance to be within $\pm 5\%$ of its average value throughout the heat-cycle test.

4.1.2. Chemical

Contacts made of base metals and contacts coated with noble metals and having pores may be subject to chemical reactions with air pollutants which cause formation of insulating films. Above a critical humidity, usually 70%, galvanic corrosion occurs at pore sites if the substrate is corrodible. Tarnish films, which may form if copper or silver reacts with elemental sulfur or with H_2S, may spread (33) from the pore sites to the remaining surface of the noble metal. Soils such as hygroscopic dust contamination and fingerprints lower critical humidity. SO_2 and certain reactive chlorine-containing pollutants, such as HCl, are aggressive at parts per billion levels.

Another humidity related degradation is silver migration from silver conductors (34): the transport of silver from one conductor to another through or on the surface of the insulator under the influence of a d-c electrical field. The positively charged conductor loses silver by oxidation in the form of positive ions, which then move through moisture paths to the cathode where they are reduced to metallic silver. The silver may grow in dendritic form and can eventually short-circuit the conductors. Current leakage between adjacent conductors through absorbed films of moisture may occur, especially if ionic contaminants are present.

Chemical degradation can be avoided by using closed structures, which may have protective covers or which may be fully hermetic, as well as by using unreactive metals. Barrier coatings are effective in some cases, and polyethylene–polybutene grease (8) is used in some splicing connectors for telecommunications cable.

Many techniques have been developed for the accelerated testing of connector contacts. These include elevated relative humidity exposure, cycling temperature–humidity procedures, and aging in chambers containing gaseous pollutants. The International Electrotechnical Commission has published a standard method for testing connectors which involves exposing the connectors for 4, 10, or 21 days in a chamber to a flowing stream of air containing 25 ppm of SO_2 at 75% rh and 25°C (15). Tests such as these, which are based on single corrosive gases, are being replaced by procedures that involve mixtures of three or four gaseous pollutants, eg, Cl_2, H_2S, NO_2, and SO_2, each at fractional ppm levels (35). Because of the complexity of environmental effects, age acceleration factors with respect to real conditions are generally unknown for tests in current use. Nevertheless, these serve as a design aid for estimating the relative merits of candidate connector contact materials and connector structures and for qualifying products.

4.1.3. Mechanical

Premature wearout or loss of contact metal during engagement and separation can result in loss of tolerances, reduced spring forces, formation of loose metallic wear debris, which may short-circuit contacts, and development of porosity in noble metal contacts. Underplatings, contact lubricants, and hard materials reduce mechanical wear.

Fretting corrosion (36, 37) can lead to high contact resistance of base metal contacts, such as tin plate in electronic connectors. Small cyclical displacements of the connector halves occur because of external vibration or differential thermal expansion and contraction of the mating contacts. The wear debris that is formed remains in the contact zone. The accumulation of oxide debris in the contact region leads to increased contact resistance. Solutions to this problem are structures that do not permit movement of contact surfaces with respect to one another, the use of gold as a contact finish, and the application of thick coatings of contact lubricants and greases, which reduce the rate of wear and restrict access of air to the contact surfaces.

Contacts containing platinum metals (see Platinum-group metals), such as palladium and rhodium, also may be subject to resistance problems from the formation of so-called frictional polymer (37) on the surfaces. This material is an insulating contaminant that originates in organic materials in the vicinity of the contact, such as organic vapors that adsorb on the surface, and subsequently polymerize to tough solids as a result of small mechanical displacements of the contacting surfaces. The thin coating of gold that usually is used on palladium and palladium alloy contact finishes significantly reduces any tendency to degrade by fretting.

5. Fiber Optic Connectors

Optical connectors are used to terminate and interconnect fiber optic cables (see Fiber optics). Transmission of information by light through optical fibers made of glass or plastic is less expensive in many cases than transmission of electric signals through wire. An advantage of fiber optic technology is that it is inherently immune from electromagnetic and radio frequency signal interference because no electrical signals are generated during lightwave data transmission. Fiber optics is popular in the telecommunication industry and there are expanding applications in the computer and aircraft and space industries.

6. Economic Aspects

Most electronic connectors are designed and made by one of the hundreds of companies devoted entirely to these products. The larger organizations both manufacture and sell internationally. In addition, this industry supports materials suppliers who provide piece parts such as metal stampings and molded connector bodies or offer a metal finishing service. The 10 largest connector companies have world sales ranging from about 300 to 2500 million U.S. dollars. These include AMP, MOLEX, AMPHENOL, 3M, ITT Cannon, Du Pont, Framatome, Hirose, Japan Aviation Electronics (JAE), and Japan Solderless Terminal (JST). Some large electrical connector users, such as those in the telecommunications, computer, and automotive fields,have captive connector manufacturing facilities and also offer products to the general trade.

The noncaptive worldwide market for electrical connectors, cable assemblies, and back panels was 19.1 billion dollars in 1992. Captive manufacture was about 31% in addition to this figure. The largest shipments were from North America, primarily the United States (38.6%); Japan (24.4%); Europe, mainly Germany, France, the UK, and Italy (25%); the Pacific Rim including Asia, mainly Taiwan, South Korea, Singapore, and Hong Kong (8.4%); and 3.6% for the rest of the world. The market is expected to increase slowly. Japan and Pacific Rim suppliers are growing in terms of their world share at the expense of North America and European suppliers (38).

BIBLIOGRAPHY

"Electrical Connectors" in *ECT* 3rd ed., Vol. 8, pp. 641–661, by M. Antler, Bell Telephone Laboratories.

Cited Publications

1. M. Antler, W. G. Graddick, and H. G. Tompkins, *IEEE Trans. Parts, Hybrids, Packag.* **PHP-11**, 35 (1975).
2. R. S. Nelson, *Multiwire Brush Contact Connector*, Report SAND 75-0245, Sandia Laboratories, Albuquerque, N.M.
3. P. Dobrogowski and J. Schroeder, III, *Proceedings of the Twelfth Annual Connector Symposium*, Electronic Connector Study Group, Cherry Hill, N.J., 1979, 233–238.
4. R. F. Mallina, *Bell Syst. Tech. J.* **32**, 525 (1953).
5. J. O. Knudson, *Proceedings of the Sixth Annual Connector Symposium*, Electronic Connector Study Group, Cherry Hill, N.J., 1973, 207–219.
6. H. B. Brown, *Proceedings of the Institute of Printed Circuits Conference*, Orlando, Fla. 1977.
7. H. J. Graff, J. M. Peacock, and J. J. Zalmans, *Bell Syst. Tech. J.* **40**, 131 (1963).
8. D. R. Frey and D. C. Borden, *Proceedings of the Second International Symposium on Subscriber Loops and Services*, London, May, 1976, 68–72 (IEEE Conference Publication No. 37).
9. R. Holm, *Electric Contacts*, 4th ed., Springer-Verlag, New York, 1967, 118–134.
10. Ref. 9, p. 8.
11. Ref. 9, 9–26, 124, 125.
12. Ref. 9, 87–92, 436–438.
13. Ref. 9, 135–152.
14. M. Clarke, in R. Sard, H. Leidheiser, Jr., and F. Ogburn, eds., *Properties of Electrodeposits, Their Measurement and Significance*, The Electrochemical Society, Princeton, N.J., Chapt. 8, 122–141.
15. M. Antler and J. J. Dunbar, *IEEE Trans. Components, Hybrids, Manufact. Technol.* **CHMT-1**(1), 17 (1978).
16. M. Antler, *IEEE Trans. Parts, Hybrids, Packag.* **PHP-9**, 4 (1973).
17. C. J. Thwaites, in F. H. Reid and W. Goldie, eds., *Gold Plating Technology*, Electrochemical Publications, Ltd., Ayr, Scotland, 1974, Chapt. 19, 225–245.
18. M. Antler, in Ref. 17, Chapt. 36, 478–494.
19. M. Antler and M. H. Drozdowicz, *Bell Syst. Tech. J.* **58**, 323 (1979).
20. M. Antler, M. H. Drozdowicz, and C. F. Hornig., *J. Electrochem. Soc.* **124**, 1069 (1977).
21. R. J. Russell, *Proceedings of the Seventh Annual Connector Symposium*, Electronic Connector Study Group, Inc., Cherry Hill, N.J., 1974, 79–94.
22. F. E. Bader, *Proceedings of the 11th International Conference on Electric Contact Phenomena*, West Berlin, Germany, 1982, 133–137.
23. A. Mendizza and P. C. Milner "Materials Technology," in *Physical Design of Electronic Systems*, Vol. **II**, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970, Chapt. 5, p. 247.
24. T. P. Piccirillo and co-workers, *Proceedings of the Holm Seminar on Electrical Contacts*, Illinois Institute of Technology, Chicago, Ill., 1976, 71–78.
25. C. Curry, *Proceedings of the Seventh Annual Connector Symposium*, Electronic Connector Study Group, Inc., Cherry Hill, N.J., 1973, 211–216.
26. C. A. Haque, *Proceedings of the IEEE Holm Conference on Electrical Contacts*, Chicago, Ill., 1989, 117–121.
27. M. Antler, *Proceedings of the IEEE Holm Conference on Electrical Contacts*, Boston, Mass., 1986, 35–44.
28. J. R. Osias and J. H. Tripp, *Wear* **9**, 388 (1966).
29. I. F. Matthysse, *Basic Connection Principles*, 2nd ed., Burndy Corp., Norwalk, Conn., 1965.
30. R. W. Barnard and J. P. Pasternak, *Proceedings of the IEEE Holm Seminar on Electric Contact Phenomena*, Illinois Institute of Technology, Chicago, Ill., 1968, 27–41.
31. J. E. Atkinson, *IEEE Trans. Reliab.*, 8 (June 1964).
32. *EEI-NEMA Standards for Connectors for Use Between Aluminum or Aluminum–Copper Overhead Conductors, EEI Pub. No. TDJ-162*, Edison Electric Institute, New York, Aug. 1973.
33. Ref. 23, p. 237.
34. Ref. 23, p. 249.
35. W. H. Abbott, *Proceedings of the IEEE Holm Conference on Electrical Contacts*, Chicago, Ill., 1987, 62–78.
36. R. B. Waterhouse, *Fretting Corrosion*, Pergamon Press, New York, 1972, 60–62.
37. M. Antler, *Wear* **106**(1–3), 5–33 (1986).
38. Technical data, *Fleck Report*, Fleck International, Huntington Beach, Calif., 1992.

General References

39. R. Holm, *Electric Contacts Handbook*, 4th ed., Springer-Verlag, New York, 1967; comprehensive treatment of electric contact theory.
40. *Connectors and Interconnection Handbook*, 5 vols., International Institute of Connector and Interconnection Technology, Inc., Anaheim, Calif.; emphasis on electronic connector design.

Comprehensive Bibliographies

41. *Cumulative Index of the Proceedings of the IEEE Holm Conferences on Electrical Contacts and the International Conferences on Electrical Contacts*, IEEE Service Center, Piscataway, N.J., IEEE Catalog Number JH 9412-8. 54 Conferences from 1953 through 1992.

Trade Publication

42. *interConnection Technology*, IHS Publishing Group, Libertyville, Ill.
43. Contributions to this paper were made by K. Fleck, M. Peel, and D. J. Williams.

MORTON ANTLER
Contact Consultants, Inc.

Related Articles

Insulation, electric; Integrated circuits; Metal surface treatments; Electrically conductive polymers