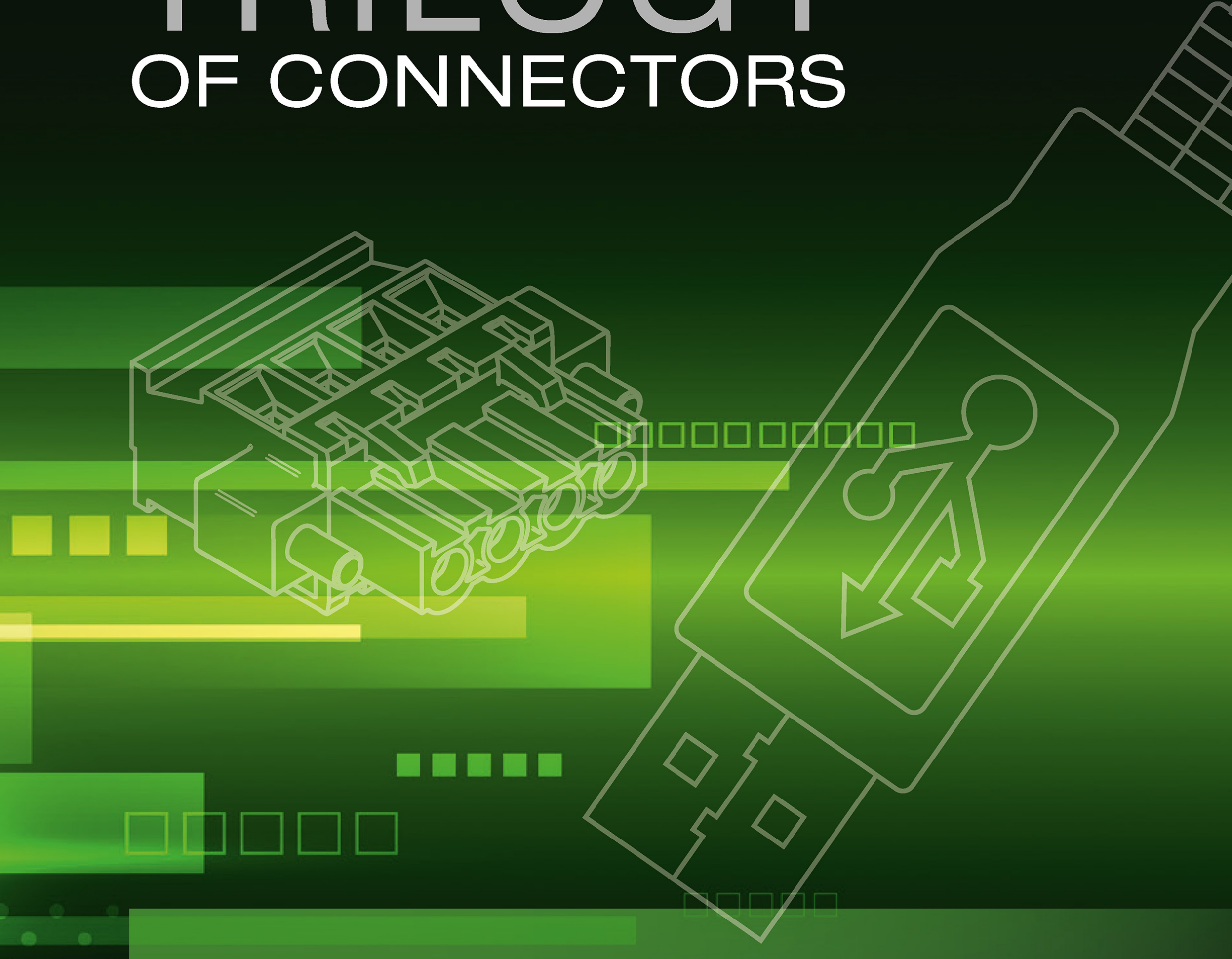
WÜRTH ELEKTRONIK

TRILOGY
OF CONNECTORS



BASIC PRINCIPLES AND CONNECTOR DESIGN EXPLANATIONS

3rd extended and revised edition

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Content

Preface

Dear readers,

I welcome you with pride to the third edition of our „Trilogy of Connectors.“ Numerous additions were made to the last edition, and now our specialist book has gradually become a mature work.

Of course, the principles about materials and contact physics are still the foundation on which application-specific knowledge is based, because a connector on close consideration is more complex than at first glance.

The third edition of our Trilogy above all has added application examples that either explain the technical basics or show the meaningful use of connectors in customer applications in order to make using them easier or to show you one or two problem-solving approaches. Moreover, some topics, for example Tin Whisker, have been expanded or, in the case of ZIF cables impedance (FCC), components were completely re-measured and the results presented as Application Notes.

Of course, to do all of this and once again meet your expectations, many experts from Product Management, our Field Application Engineers, and above all our customers were involved who supported us with application examples. I‘d like to thank them especially for taking time to let us profit from their experiences and for sharing their knowledge.

I look forward to your comments and hope you enjoy reading the book!

Sincerely,

Thomas Robok

Würth Elektronik eiSos GmbH & Co. KG

Thank you! / The Authors

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Dr. Robert S. Mroczkowski, founded connNtext associates in 1998, a firm providing consulting services in connector applications to the electronics industry. Dr. Mroczkowski has more than 30 years experience in the electronics industry. He joined AMP Inc. in 1971. While at AMP, his responsibilities included consulting on connector design, materials, and reliability concerns, and he provided an interface to AMP customers on these issues. In 1990 he joined the AMP Advanced Development Laboratories, where he developed microstrip cable connectors and a new microcoaxial connector for medical ultrasound diagnostic equipment. Dr. Mroczkowski retired in 1998 as an AMP principal. He wrote more than 20 technical papers. He holds seven patents. In 1997, Dr. Mroczkowski received the Lifetime Achievement Award of the International Institute of Connector and Interconnection Technology. He holds a bachelor's, master's, and doctorate of science degrees in physical metallurgy from the Massachusetts Institute of Technology (MIT).

Romain Jugy, born in 1975. He has worked in the field of connectors for more than 10 years. He started at Radiall where he was coaxial connector product manager. He was then a successful international product manager at HARTING where he was in charge of launching D-Sub filters and other I/O connectors. Since 2005, he has been the person in charge of internationally developing the Würth Elektronik connector range and he is now head of the connector product management at Würth Elektronik. He has an engineering diploma in Chemistry and Material (ENSCM Montpellier), as well as a Master in Marketing and Company Administration (IAE Montpellier).

Alexander Gerfer, born 1965, worked in the field of research and development for precision measuring instruments following his training as a radio and television technician. This was followed by a degree on electrical engineering at the Technical University of Cologne. While studying, Alexander Gerfer published numerous application circuits and construction guidelines from the field of consumer electronics. After his degree, he worked in electronic component distribution and since 1997, he is head of R&D department at Würth Elektronik.

Trilogy of Connectors

Basic Principles

Basic principles and connector design explanations for an optimized connector selection

I Basic Principles

Part 1: Basic Principles

1 Basic Principles of Connectors

A list of electrical or electronic devices using connectors would be long and varied both in function and construction. At the beginning of the list, both in function and construction, is an incandescent lamp. At the complex end of the list, both in function and construction, is a collection of computer servers interconnected to provide the immense functionality of a search engine.

Let's take the easiest example, the function of an incandescent lamp is to provide light by passing an electric current through a filament, a technology developed in the late 19th century. While the functionality and technology of the various servers linked together in a search engine is beyond the scope of this handbook, it must be noted that its construction includes a power source and a multitude of electronic devices that must be connected together.

The common link between the two examples is interconnections, interconnections provided, in some manner, by connectors. Every electrical or electronic device includes at least one connector, the interconnection between the power source and a functional device. The discussion will begin with the incandescent lamp system which contains all the basic connector construction and functionality issues in a search engine, but at a more accessible level. The search engine will be discussed later in terms of the various levels of interconnection in electronic devices and equipment.

The example incandescent lamp system shown in Figure 1.1 includes a power source, the house wiring, and a wall receptacle/plug, arguably the most familiar connector, which provides the interconnection between the power source and the lamp. There are two types of connections shown in Figure 1.1.

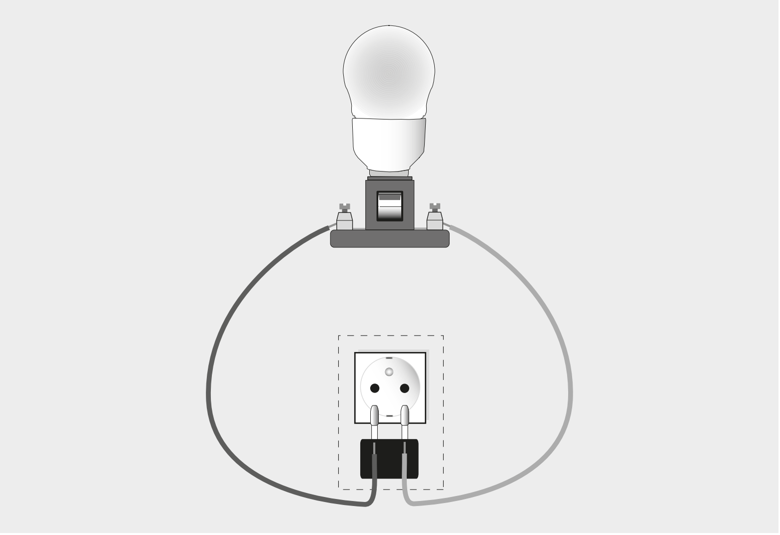


Fig. 1.1: Incandescent light

Separable connection

The power connection consists of two sections the wall receptacle and the wall plug. This connection is a **separable connection**, the wall plug is separable from the wall receptacle to enable the lamp to be moved to different locations. The wall plug has two metal pins that are inserted into the wall receptacle and the wall receptacle contains two metal spring systems that are deflected as the pins are inserted. Two pins/receptacle springs are necessary to provide both input and output power connections. The force created by the deflection of the receptacle spring when a pin and the receptacle spring come in contact creates and maintains the metal-to-metal interface that enables the power, voltage and current, from the power source to be transmitted to the lamp. The properties of this interface will be discussed in detail later in this chapter, but it is worth noting at this point **that creating and maintaining a metal-to-metal interface is the prime goal of connector design**.

Permanent connection

Connector

In addition to this separable connection, there are two **permanent connections**. The wall receptacle is connected to the house wiring, usually by a mechanical connection. Similarly, the wall plug is connected to the lamp cord wiring, also through a mechanical connection. **These two types of connections, separable and permanent, are characteristics of connectors**.

1.1 Connector Function

With this basic introduction to connectors in hand, consider now a more detailed introduction to connectors and the components of a connector. A functional definition of a connector is:

A connector is an **electromechanical** system which provides a **separable connection** between two subsystems of an electronic system without an **unacceptable effect** on the performance of the device.

The bolded terms in this definition are the most significant characteristics of a connector.

A connector is an **electromechanical** system in that it creates an electrical connection by mechanical means. As previously mentioned, deflection of mechanical springs creates a force between the two halves of the connector on mating which creates areas of metal-to-metal contact at the mating interface. The metal-to-metal interface provides the connection where the current flow takes place.

A separable connection, separability, is the primary reason for using a connector. Separability may be required or desirable for a variety of reasons. Manufacturability considerations include allowing for independent manufacturing of subassemblies or subsystems with final assembly taking place at a central location. As the complexity and functionality of electronic systems continues to increase this manufacturing flexibility is increasingly important. One example is the ability to “custom build” a personal computer to your own specifications. A second example is to allow for maintenance or upgrading of components or subsystems as increased functionality becomes necessary. Finally, portability and the ability to support an increasing range of peripherals in a laptop computer require separable connections for multiple use of an input port or usage at multiple locations. The number of **mating cycles**, mate and unmate, needed depends on the reason separability is required. Manufacturability reasons generally require only a few mating cycles while portability and multiple port usage may require several hundred mating cycles in a laptop computer.

Mating cycle

While these separability capabilities are virtues, separability, by definition, introduces an additional interface into the system. This interface must not introduce any **unacceptable effects**, in particular any unacceptable electrical effects, on the system performance. The most significant potentially unacceptable electrical effect relates to the resistance across the mating interface: both the magnitude and stability of the resistance. Resistance increases are of particular importance in power transmission for two reasons. First, the Joule, or I^2R, heating as current, I, flows increases as the electrical resistance, R, increases. Joule heating increases the temperature of the contacts which, in turn increases the degradation rate of the interface, up to and including, melting or open circuiting of the interface. Second, large increases in resistance can impact the signal transmission characteristics in digital applications. Thus, the magnitude and stability of the resistance across a mating interface is a major consideration in connector performance and reliability. Interface resistance will be discussed in detail later in this chapter.

1.2 Connector Structure

Consider now a structural definition of a connector. There are four basic components in a connector. They are:

A. **the connector housing**
B. **the contact springs**
C. **the contact finish**
D. **the contact interface**

This chapter will provide a basic introduction to connector housings, contact springs and contact finishes with details to be provided in following chapters. The contact interface will be discussed in detail in this chapter.

A few general comments are appropriate at this point. All connectors consist of two mating halves, a plug half which is inserted into the receptacle half. This plug/receptacle structure exists in both the housings and the contact springs. With respect to the contact springs, as mentioned earlier, in most connectors the plug contact deflects a spring system in the receptacle contact. This spring deflection produces the contact force which creates and maintains the desired metal-to-metal contact interface.

Plug
Receptacle

Consider these components as realized in a wall plug/receptacle connector as shown in Figure 1.2. The housing of the plug connector is overmolded onto the straight copper alloy plug contacts which are crimped onto the lamp cord wire. The housing of the

Contact

receptacle connector is assembled around the copper alloy receptacle contacts which are pressure connected to the house wiring. When the connector halves are mated, the receptacle contact spring is deflected by the plug contact creating the contact interface. In this example, there is no contact finish, no plating or coating, on the contacts. The functions of a contact finish will be discussed in a following section.

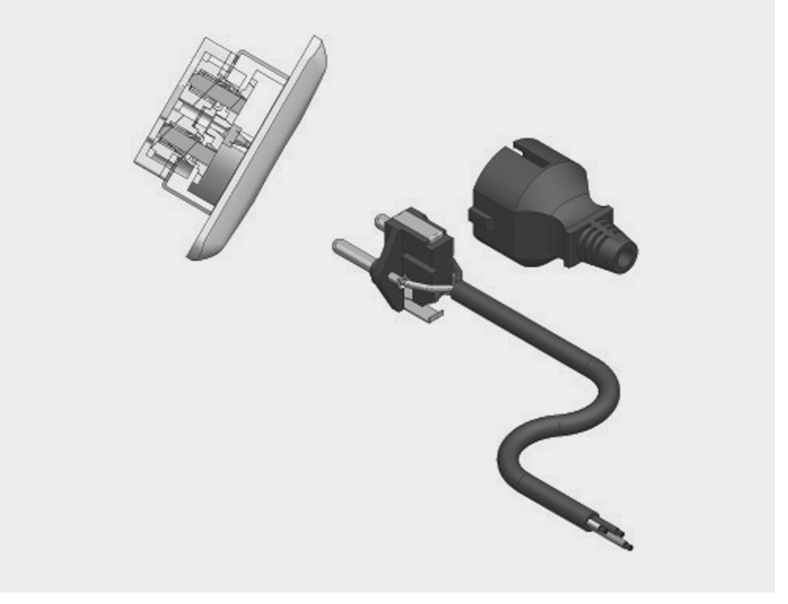


Fig. 1.2: Components of a wall plug/receptacle connector

A cross section of a more typical connector is shown in Figure 1.2 with all components illustrated. Each of the connector components will be discussed briefly in this chapter and in detail in the following chapters.

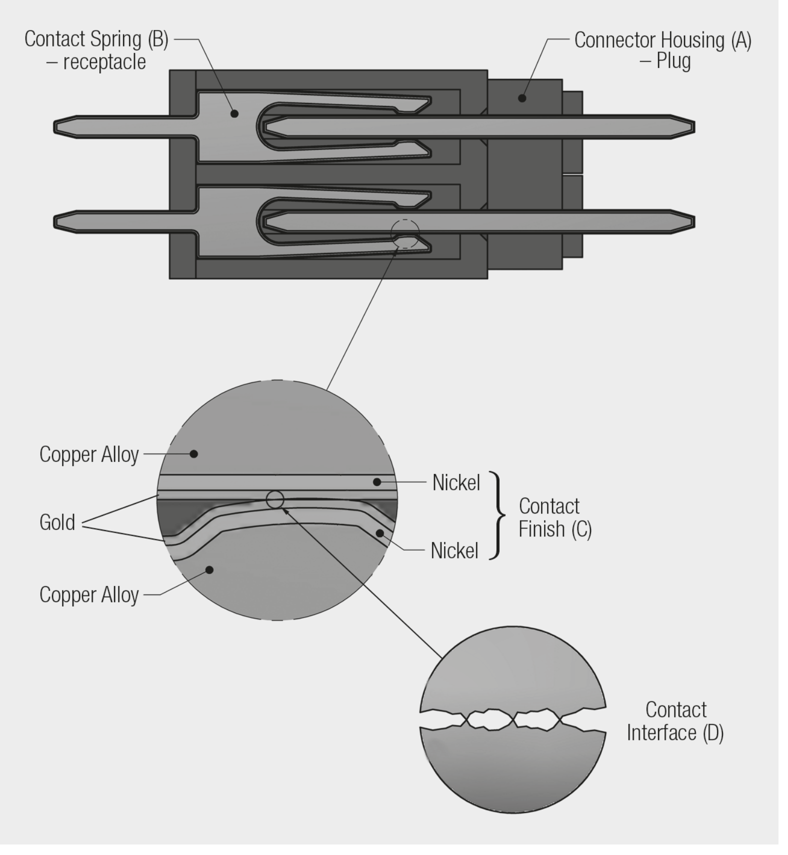


Fig. 1.3: Schematic connector cross section

1.2.1 Connector Housing

The connector housing, A in Figure 1.3, is the most obvious connector component and has four major functions:

Electrical insulation
All connectors have at least two contacts, input and output, which must be electrically insulated from each other. Most connectors have many more positions providing power or signals to the functional elements of the device. These multiple positions, too, must be electrically insulated from each other. Socket connectors for integrated circuit packages, for example, are available with more than a thousand positions. The insulation characteristics of a connector housing are dependent on both the design and material of the housing as will be discussed in Chapter II.

Dimensional stability
The two halves of the housing must mate together and, therefore, their mating features must be of corresponding shapes and on the same centerlines. The dimensional control required, obviously, depends on the size and the centerline spacing of the housing.

Centerline spacing

Centerline spacings can vary from 0.3 mm (0.100 in) to 10 mm or even higher with corresponding decreases in dimensional tolerance requirements. The ability to realize these levels of dimensional control, both during molding of the housings and in field applications is an important consideration in housing design and material selection.

Mechanical support
In many connector designs the contacts are “latched” into the housing for mechanical support as well as dimensional control. Because spring deflections are responsible for creating the contact force, the mechanical stability of the support provided by the connector housing can have a significant impact on the spring characteristics of such connectors. Once again, this requirement impacts on the design and materials choices for the housing.

Environmental shielding

Corrosion

Most contact springs are made from copper alloys which are susceptible to corrosion reactions with oxygen, sulfur and chlorine, all of which are present in typical connector applications. Details of these processes will be provided in the second part of this chapter, Contact Finishes. At this point, it suffices to say that the design of the connector housing can have a significant impact on the environmental stability of a connector by shielding the contacts and contact interfaces from the environment.

Figure 1.4 illustrates this shielding effect. The coupon shown is a copper plate. The coupon shown was exposed to a sulfur bearing environment while mated with the ZIF connector shown. Note the severe corrosion of the exposed portion of the coupon as compared to the shiny surface of the portion contained within the housing. Note also the wiping marks made by the receptacle contact springs as the coupon is inserted into the connector. This illustrates the cleaning effect that occurs during mating to wipe away surface films and contaminants.

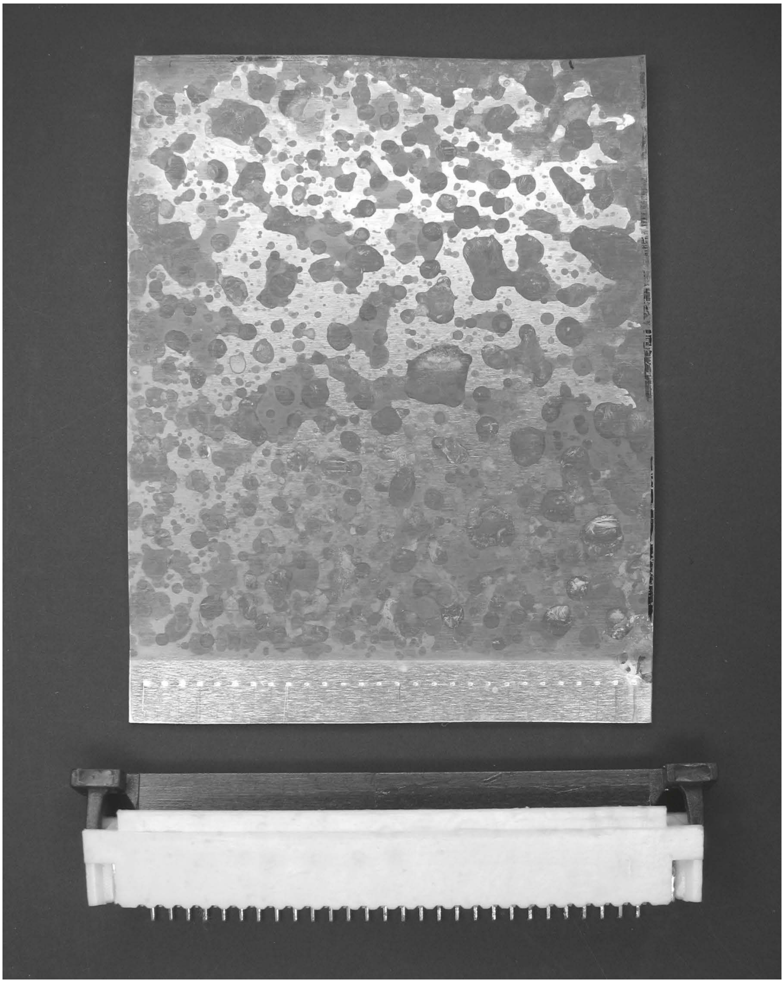


Fig. 1.4: Copper coupon[1]

More important, however, is the data shown in Figure 1.5. This data will be discussed in detail in Chapter II/2.1 Contact Finishes. At this point it is sufficient to note that the data showing significant increases in contact resistance was from connectors which were exposed to the test environment **unmated**. That is, the plug and receptacle halves were exposed separately, while the stable resistance data was taken from **mated** connectors. The effectiveness of housing environmental shielding is clear. The shielding effect of connector housings provides an important contribution to the ability of connectors to remain functional in harsh environmental applications.

1 Mroczkowski, R. S.: "Corrosion and Electrical Contact Interfaces", NACE, Corrosion 85, 1985

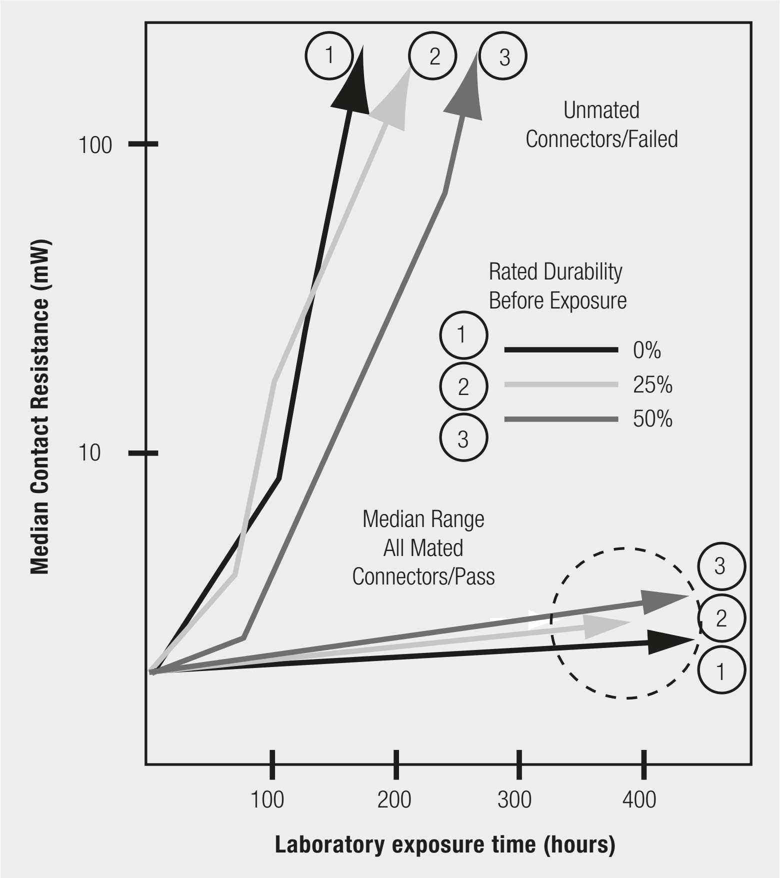


Fig. 1.5: Resistance data

Header

Connector housings vary in pin count from one to over a thousand, and in complexity from simple headers, Figure 1.6, to housings incorporating channels for air flow, Figure 1.7. Connector housing design, material selection and manufacturing practices will be reviewed in Chapter II/Design/Selection/Assembly.

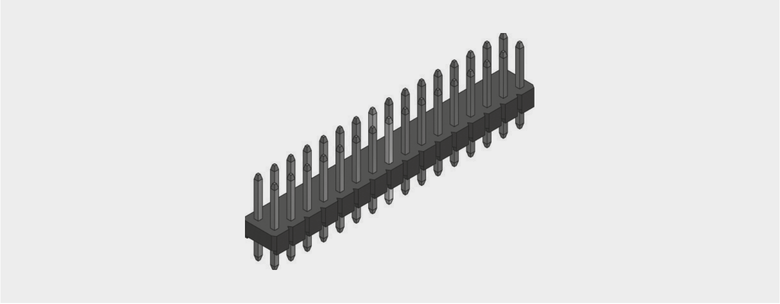


Fig. 1.6: Pin Header

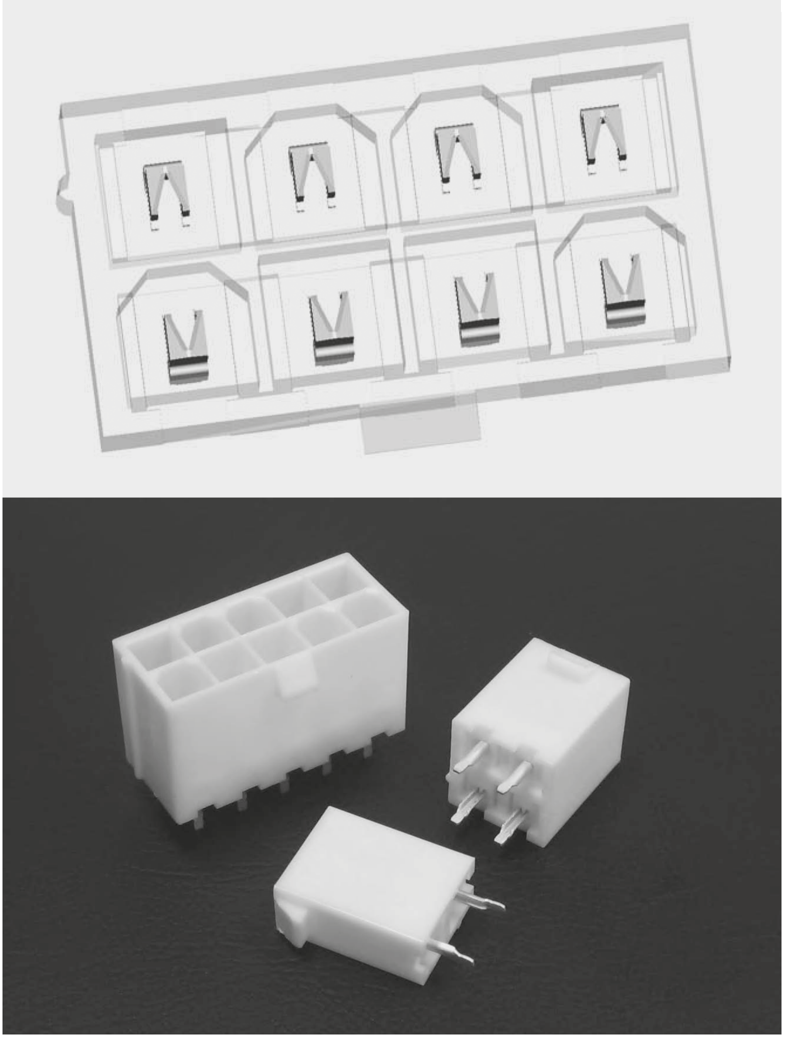


Fig. 1.7: Mini power connector top view (gap for air flow area)

1.2.2 Contact Springs

The contact springs, B in Figure 1.3, are typically manufactured from copper alloys in order to provide three major functional capabilities:

Electrical conductivity

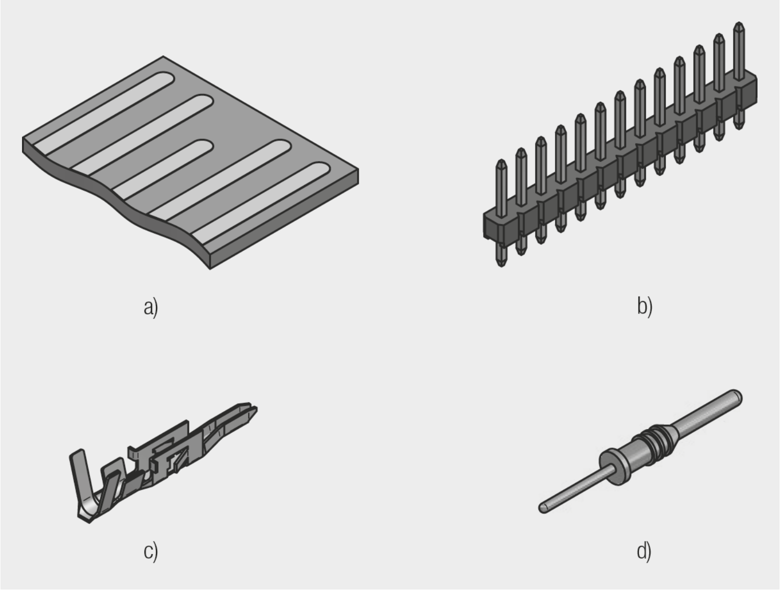
Electrical conductivity
The contact springs provide the electrical connection between the two sub-systems being connected. Copper alloys provide the highest electrical conductivity of commonly used metals when we consider the material price as well.

Separable Connections and Contact Force

Contact normal force

As mentioned previously, the separable contact interface in a connector is created and maintained by the contact normal force generated by deflection of the receptacle contact springs by the plug contact on mating. **For this reason, the contact normal force is arguably the most important connector design parameter as will be discussed in seperable connection chapter.**

Plug contacts, Figure 1.8, include pads on a printed circuit board and rectangular or round pins, respectively. Receptacle contacts come in a variety of spring geometries to serve different application needs and requirements.



Plug

Fig. 1.8: Plug contacts

Figure 1.9 shows several receptacle spring geometries intended to provide functional capabilities, such as accommodating tolerances, and controlling the range of contact force in the connector. Copper alloys provide a good balance of spring characteristics and manufacturability. All of these contacts mate to a pin or post but require different amounts of forming to provide performance enhancements. Figure 1.9a is a simple flat stamping having twin cantilever beam contacts. The limitation of this contact is that the mating surfaces are the sheared edges of the stamping. This means a rough and uneven mating surface which is undesirable. If the contact was to be tin plated it could be used as is. But if silver or gold plating is desired the sheared edge would have to be improved eliminating the cost advantage. Figures 1.9b and 1.9c are simple means for eliminating the sheared edge issue. In Figure 1.9b the contact beams are simply twisted by 90 degrees so the mating surface becomes the rolled surface of the strip. The spring system is no longer a simple cantilever beam due to the twist which stiffens the beam. In Figure 1.9c the contact beams are folded upward to make the contact surface a rolled surface. The spring system is no longer a cantilever beam. The beam deflection will also open the U shape at the base of the beams. Finally, Figure 1.9d includes multiple forming operations to provide a crimped permanent connection with an insulation grip, latching beams to retain the contact in the housing and a box entry which provides an alignment feature as the pin or post is inserted into the contact.

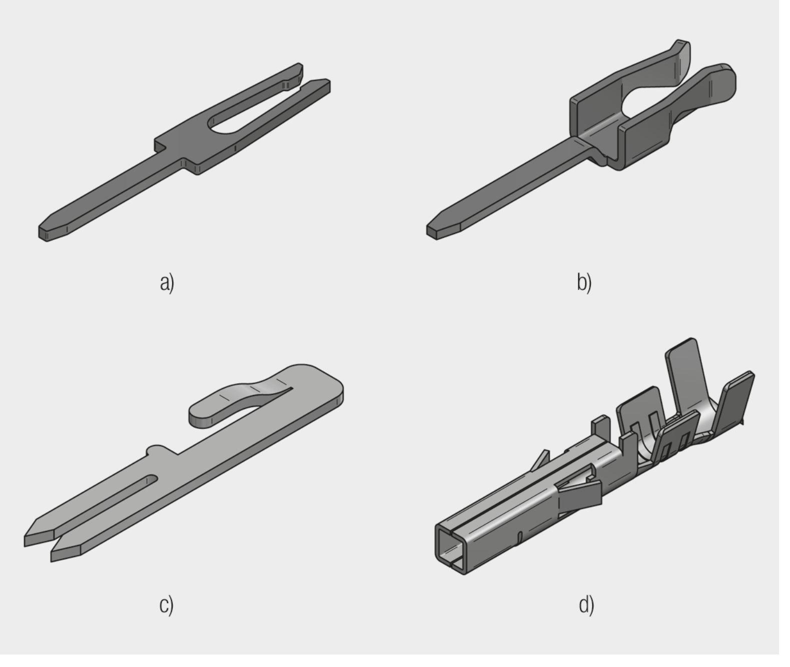


Fig. 1.9: *Receptacle* contacts

Receptacle

Permanent connections

Permanent connection

A connector also includes permanent connections between the connector contacts and the sub-systems being connected. Permanent connection methods used in connectors include both metallurgical and mechanical technologies. The primary metallurgical permanent connection method is soldering. There are two basic soldering technologies used in connectors, through hole and surface mount, examples of which are shown in Figures 1.10 and 1.11 respectively. The long solder tails in Figure 1.10 are inserted into plated through holes in a Printed Circuit Board (PCB) and wave soldered. The solder tails in Figure 1.11 are reflow soldered to surface pads on a pcb. Wave and reflow soldering will be reviewed in Chapter II/Design/Selection/Assembly. The two major mechanical permanent connection technologies are crimping and insulation displacement, examples of which are shown in Figures 1.12 and 1.13 respectively. Crimp and IDC technologies will be reviewed in Chapter II/Design/Selection/Assembly. Copper alloys are advantageous for both metallurgical and mechanical permanent connections because they are solderable/weldable and readily stamped and formed into the configurations needed to create mechanical permanent connections. Details of these technologies will be provided in Chapter II/2.2.2 Permanent Connections area. Details on copper alloy selection and manufacturing technologies as applied to connectors will be discussed in Chapter I/1.4 Connector Materials and Processes.

Soldering

Crimping
IDC

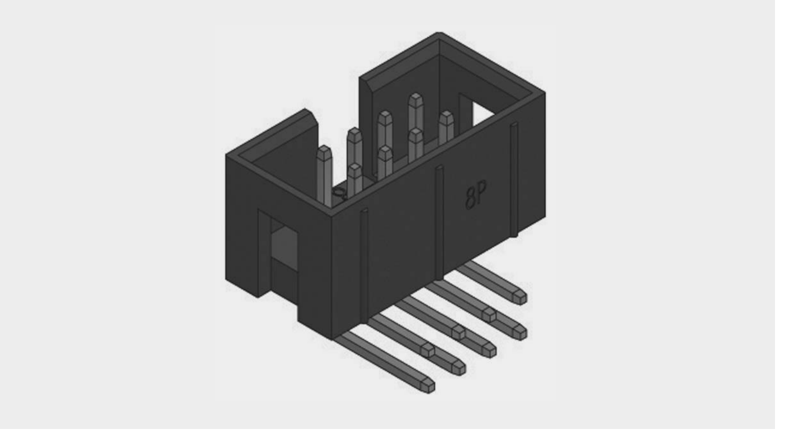


Fig. 1.10: Through hole box header

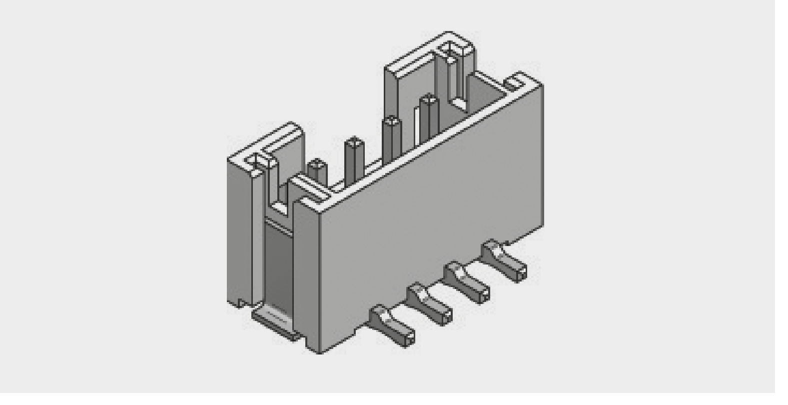


Fig. 1.11: SMT wire to board connector

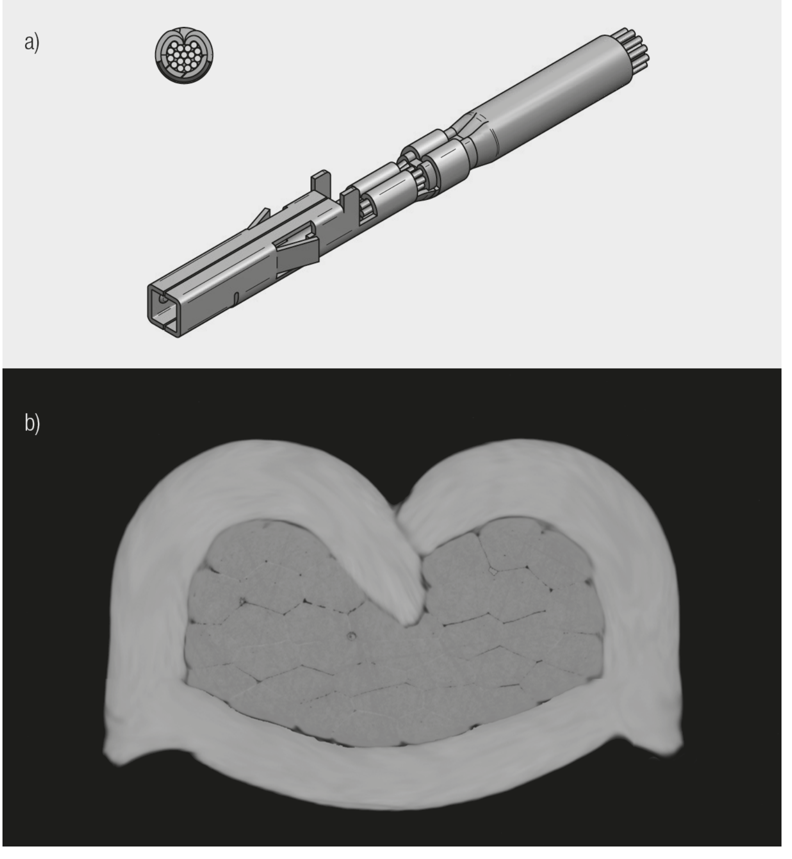


Fig. 1.12: Crimped permanent connection

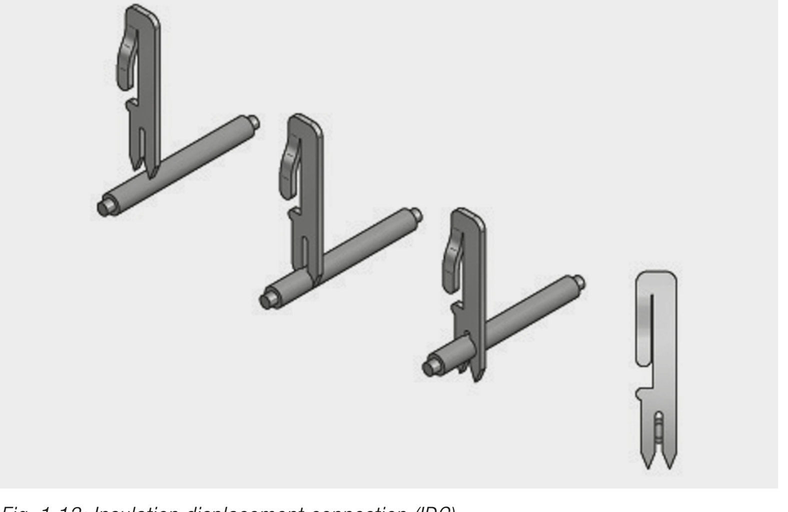


Fig. 1.13: Insulation displacement connection (IDC)

1.2.3 Contact Finishes

Contact finish

A contact finish, C in Figure 1.3, consists of a surface coating, generally produced by electroplating, over the contact spring to provide two performance benefits: Corrosion protection for the contact springs and optimization of the electrical and mechanical characteristics of the contact interfaces. As mentioned, copper alloys are typically used as connector contact springs and are susceptible to corrosion in typical connector operating environments. The contact finish provides corrosion protection by covering the exposed copper to protect it from the operating environment. "Optimization" of contact interface performance is provided by influencing the corrosion and wear characteristics of the contact interface. These functions will be discussed in Chapter II.

Noble metal

There are two general types of contact finishes, noble and non-noble. Gold is the predominant noble metal finish material. The term "noble" refers to the fact that gold is not susceptible to corrosion. Tin is the most common non-noble finish material. Tin is susceptible to corrosion by the formation of a thin self limiting thickness of tin oxide. This oxide protects the contact interface from further corrosion, but is readily displaced on mating of the connector to provide the desired metal-to-metal contact interface. A brief overview of each finish will be provided here with details to follow in Chapter II/2.1 Contact Finishes.

1.2.3.1 Noble Contact Finishes

A noble metal finish is a system consisting of three components. A surface coating of noble metal, gold or palladium alloy, an underplate, generally nickel, and the base metal of the contact spring as shown in Figure 1.14. For Telecom or harsh environment gold and nickel are typically electroplated to thicknesses of the order of 0.4 to 0.8 µm (15 to 30 microinches) for gold and 1.25 to 2.50 µm (50 to 100 microinches) for nickel. Noble metal finishes are used in high performance and high reliability applications.

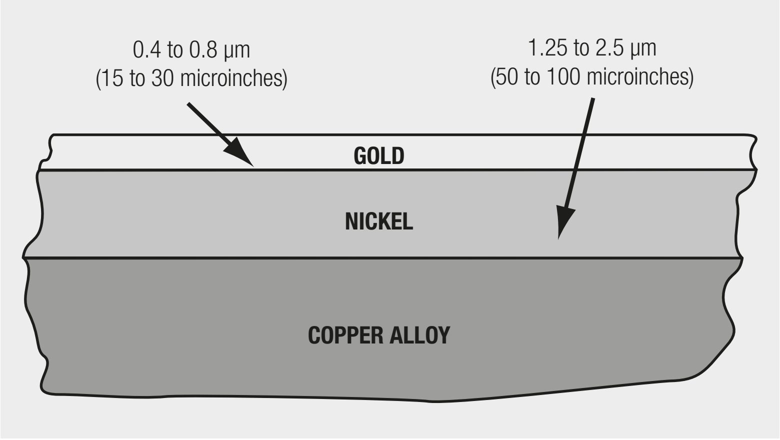


Fig. 1.14: Noble metal contact finish

The gold top coat provides the corrosion protection. It also allows for performance optimization in that the hardness of the gold can be controlled to influence the friction and wear behavior of the mating interface.

The nickel underplate provides several performance advantages noted here for reference with details to follow in Chapter II/Design/Selection/Assembly.

The nickel underplate:

- **reduces the susceptibility to pore corrosion**
- **reduces corrosion migration**
- **provides a diffusion barrier to base metal migration**
- **improves the mating durability of the contact interface**

Nickel underplate

Durability

The contact spring is included in the noble metal finish system for both electrical and mechanical reasons. The electrical reason is that the distribution of the current flow to the contact interface is dependent on the conductivity of the contact spring. The mechanical reason is that the stresses applied to the contact interface during mating can extend down into the spring material due to the small thicknesses of the gold and nickel platings.

1.2.3.2 Non-noble Contact Finishes

The dominant non-noble finish is tin, with silver and nickel being used in selected applications. Tin is used in industrial and commercial applications including white goods, while nickel and silver are primarily used in battery contact and power contacts respectively.

These finishes are also typically electroplated, but tin can also be applied by dipping or reflow processes. Tin finish thicknesses are in the range of 2.5 to 5.0 µm (100 to 200 microinches). Nickel and silver thicknesses are generally in the range of 1.25 to 2.5 µm (50 to 100 microinches).

1.3 The Contact Interface and Contact Physics

1.3.1 Overview

The contact interface, D in Figure 1.3 is arguably the heart of a connector system. The structure and properties of the interface which is created as the plug and receptacle contact springs come together determines both the electrical and mechanical performance characteristics of a connector.

The most important characteristic of the contact interface is that it is created when two rough surfaces come into contact. While a cursory look at the surfaces of contact springs suggests that they are smooth, on the microscale of the contact interface these surfaces are quite rough. The individual high points on the surface are referred to as asperities. Figure 1.15 schematically illustrates the contact interface that would

Asperity
a-spot

be created if two spheres were brought in contact under an applied load. As the two surfaces approach each other the asperities that happen to be in proximity to each other come together first. As these asperities deform against each other under the applied load, the surfaces continue to approach each other bringing additional asperities into contact. Thus, a contact interface consists of a number of individual asperity contact points, called **a-spots**. The number is determined by the roughness of the surface and the applied load which determines the total area of a-spot contact. These a-spots are distributed over an apparent contact area that is determined by the geometries of the post and receptacle contact springs as they come together.

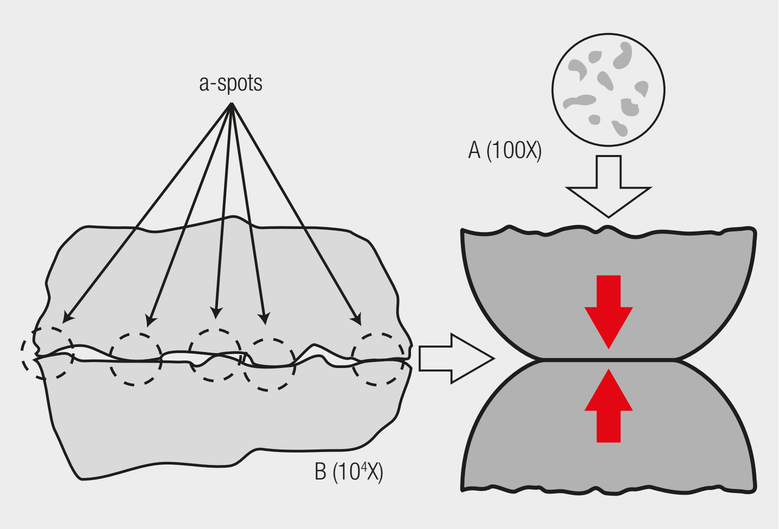


Fig. 1.15: Schematic contact interface

That this a-spot model is realistic is verified by consideration of Figure 1.16 which shows an actual contact interface between a stainless steel ball bearing and a glass plate. The ball bearing deforms slightly against the glass plate under the applied load and individual a-spots are created. Note the similarity to Figure 1.15. The photo on the right was taken after an increase in the applied load which brings the surfaces closer together. This, in turn, increases the contact area of existing a-spots as well as creating additional a-spots.

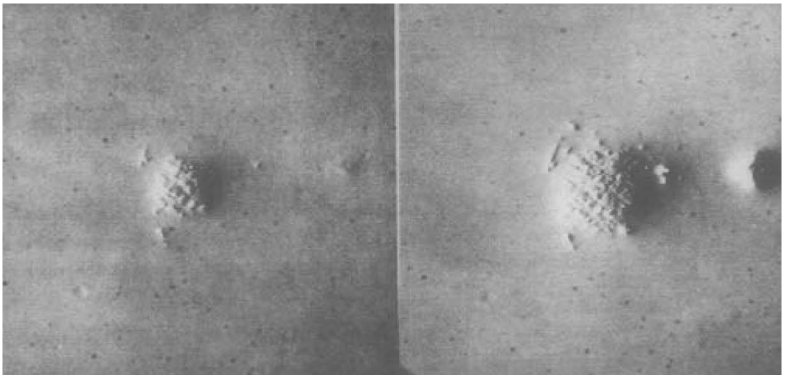


Fig. 1.16: Contact interface at increased load[2]

Returning to Figure 1.15, a side view of the contact interface, also shows a distribution of a-spots across the contact interface. This view will lead to an understanding of why the contact interface structure affects both the mechanical and electrical performance.

Consider two mechanical effects. First, if a shear stress is applied to this a-spot contact interface the interface will remain stable until the stress is sufficient to break the a-spot interfaces. Second, when the interface does break a wear process comes into play. These two effects will be discussed in Chapter I/1.3.2 The Mechanical Interface: Friction and Wear/Durability.

Electrical performance is affected by the fact that any current flow from the upper sphere to the lower, would have to flow through the individual a-spots. This condition leads to an electrical resistance called **constriction resistance** which will be discussed in some detail in Chapter I/1.3.3 The Electrical Interface: Contact Resistance.

1.3.2 The Mechanical Interface: Friction and Wear/Durability

Friction
Wear

Friction and wear are two aspects of the same basic kinetic process. Friction forces must be overcome to cause motion, and motion must occur to cause wear. Consideration of Figure 1.17 will be used to explain this statement.

[2] Courtesy J. B. P. Williamson

Adhesive wear

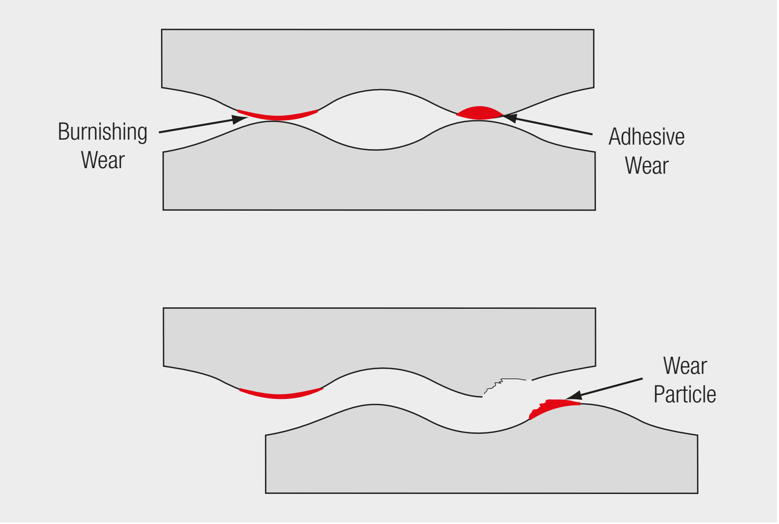


Fig. 1.17: a-spots and friction wear

Consider Figure 1.17 through a thought experiment where two a-spot contacts are created. The a-spot on the right is created first under a given applied load. The individual asperities deform against each other under the load. Four things happen during the deformation. First, the asperities deform plastically due to their small size causing material flow. Surface films and contaminants are disrupted or displaced on the microscale of the flow. Second, the clean metal surfaces exposed due to the microflow can form cold welded junctions[3] when the microflow ceases. Third, the asperity surfaces work harden due to the deformation. Fourth, the a-spot contact area increases as the load increases.

While all this is happening at the first asperity contact the surfaces are continuing to come closer to one another and the second a-spot is created. The same process then begins to take place at this second a-spot. We now have two a-spots that have experienced different amounts of deformation. The difference in deformation means that the first a-spot is larger, due to more metal flow, and stronger – due to a greater work hardening response and more cold welding.

The increased area and strength of the first a-spot means that it will be mechanically more robust. Consider how the two a-spots will respond under an applied shear stress. This discussion is qualitative and only serves to illustrate the kinetics of friction and wear.

The applied shear stress will not lead to motion of the interface until the a-spots are broken. Given that the first a-spot is larger and stronger, it will determine the stress necessary to break the interface and cause motion. The necessary stress is related to

[3] A cold weld results when two clean metal surfaces come in contact as a result of the fact that metallic bonding forces are non-directional. Surface atoms extend bonding forces into space and the bonding forces from two surfaces in proximity interact to form a cold weld.

the friction force of the contact interface. Thus the a-spot structure and distribution determines the friction force and, therefore, the mechanical stability of the contact interface.

The kinetics of separation at the a-spot interfaces will be different as well. Recall that the interface of the first a-spot is stronger than that of the second. In fact, due to work hardening and cold welding, the interface may be even stronger than the cohesive strength of the base metal. In such cases, the a-spot interface may break within the base metal rather than at the interface resulting in a wear particle as indicated in Figure 1.17. Such wear processes are commonly referred to as **adhesive wear**. In contrast, the weaker interface of the second a-spot may break at or near the original interface without a wear particle being generated. Wear of this type is referred to as **burnishing wear**. The wear track in a connector experiencing adhesive wear, sometimes called galling wear, will be rough, while that of burnishing wear will be relatively smooth.

Adhesive wear

Burnishing wear

The significance of wear processes in a connector is straightforward. **Wear results in the loss of surface material.** If a connector is designed to take advantage of the benefits of a contact finish, wear can lead to loss of the contact finish at the mating area and a consequent decrease in performance. This is particularly significant when the small thicknesses of contact finishes are recognized. **Susceptibility to wear is one reason connectors are rated for a specific number of mating cycles.**

Friction has two effects on connector performance, one positive and one negative. The positive effect is that friction provides mechanical stability of the contact interface against forces tending to drive motion of the connector. Disturbances of the contact interface can be a significant degradation mechanism for a connector for two reasons. First, the micromotions of a contact disturbance can induce wear at the contact interface. Second, micromotions can drive corrosion mechanisms, especially in tin finished contacts, and can lead to bring corrosion products and contaminants around the contact area into the contact interface. Thus high friction forces, generally due to high contact normal forces, can have a positive effect on connector performance.

There are two negative effects of friction forces. First, high friction forces correlate directly with wear mechanisms as has been discussed. Second, high coefficients of friction will increase the mating force of a connector. **Mating force varies directly with the coefficient of friction.**

These issues, friction, mating force, contact force and wear will be discussed in detail in Chapter II/2.2.1 Separable Interface Requirements.

1.3.3 The Electrical Interface: Contact Resistance

Contact resistance

Attention now turns to the effects of a-spots on electrical performance, and, in particular on the electrical resistance the contact interface introduces into the connector. To address that issue requires a discussion of the sources of resistance in a connector.

Figure 1.18 shows a cross section of a connector with the various sources of resistance indicated. There are three types of resistances noted. There are two permanent connection resistances $R_{P.C.}$, the resistance of the crimped connection to the incoming conductor and of the pin connection to the plated through hole of the printed circuit board. Permanent connection resistances are dependent on the permanent connection technology used. There are also two bulk resistance contributions R_B, from the pin and receptacle contacts individually. Bulk resistances are determined by the resistivity of the material of the contact spring and its geometry. Finally, there is the resistance of the contact interface R_C. Only one resistance is cited even though there are two contact interfaces electrically in parallel.

Bulk resistance

Contact Resistance

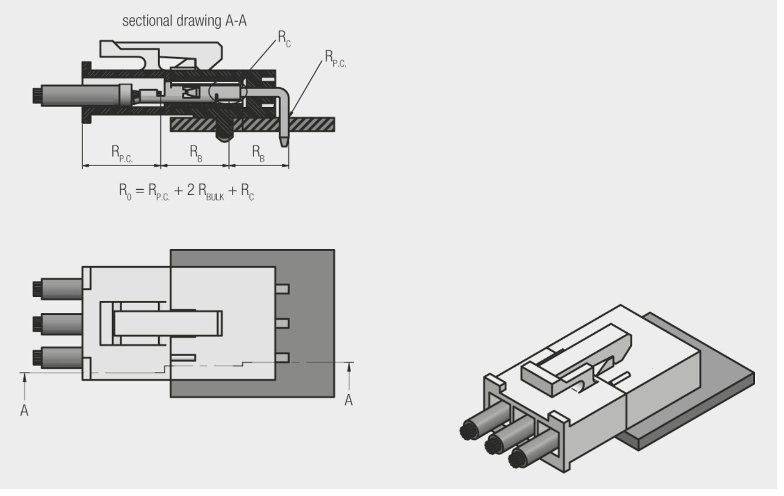


Fig. 1.18: Connector resistance

In order to get a perspective on the relative contributions of these three resistances, consider the following thought experiment. If a test probe is inserted through the insulation to the conductor of the wire coming into the crimped connection and a corresponding probe placed in contact with the pad on the plated through hole connection the overall resistance $R_{overall}$ of the connector can be measured. To provide a benchmark, it is assumed that the connector system shown uses a 0.64 mm (0.025 in) square post. For a connector of this size a reasonable value for the overall resistance is of the order of 20 milliohms. The permanent connections will be less than a milliohm each, the bulk resistances will total about 17 milliohms and the contact resistance will be of the order of a milliohm. Thus, for this connector system the contact interface resistance is of the order of five percent of the overall resistance. **Why then is the contact interface resistance so important?** The answer is found when the connector system is subjected to a test program to assess its stability under a variety of conditions. If, after such testing, the overall resistance of the connector is measured and found to be, say, 200 milliohms virtually all that change will be in the contact interface resistance.

Bulk resistances are essentially constant. Permanent connection resistances tend to be stable because they have larger contact areas and contact forces than separable interfaces. **So, an understanding of the parameters that determine contact interface resistance is critical to knowing how to design and maintain its integrity over the broad range of connector applications and application environments.**

As noted previously, electron flow can only occur through an a-spot, the majority of the apparent contact area is non-conductive. This means that the current distribution through the contacts is constricted to pass through individual a-spots at the contact interface. This geometrical current constriction gives rise to constriction resistance as illustrated in Figure 1.19.

Constriction resistance

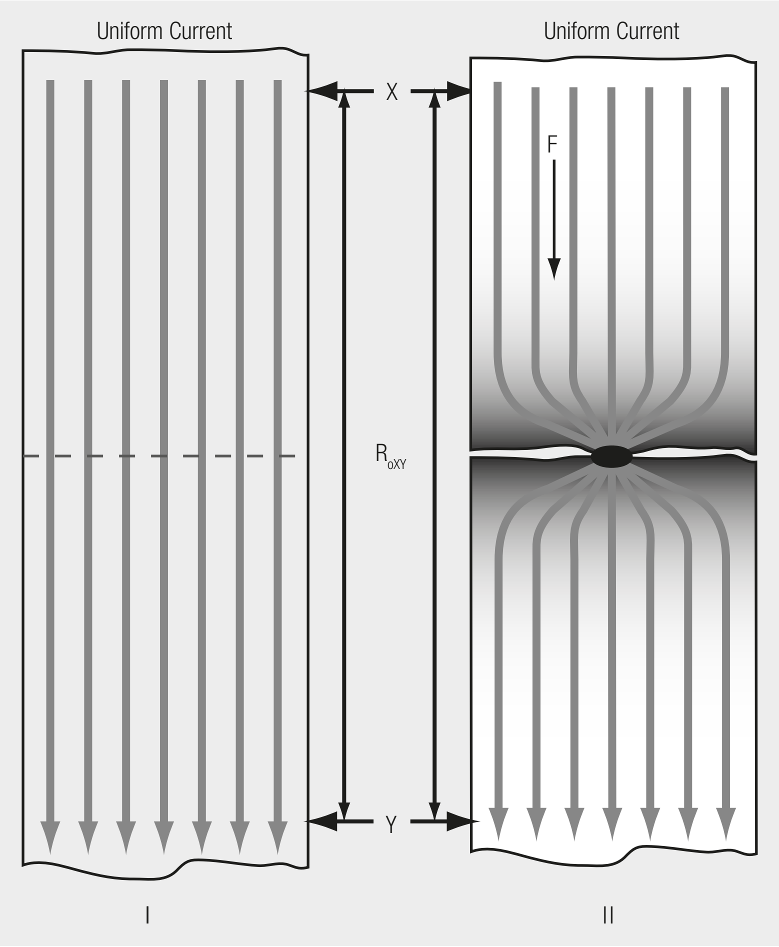


Fig. 1.19: Constriction resistance

Another thought experiment. The drawing on the left in Figure 1.19 depicts a length of round conductor. Voltage and current probes are connected to the conductor at points X and Y so that a direct current voltage can be applied between points X and Y and the resulting current measured. Ohm's law, V = I R, where V is the voltage drop, I is the current and R the resistance, can be used to calculate the resistance.

An additional, independent, way to calculate the resistance is using the below relationship: where ρ is the resistivity of the conductor material, L the length between X and Y and A is the cross sectional area of the conductor. Naturally, these two methods result in the same value of resistance.

Ohm's law

$$R = \rho \, (L/A) \qquad (1.1)$$

Now for the thought part. Assume that a zero thickness blade can be used to cut into the conductor midway between X and Y down to an infinitesimal distance from the center of the conductor. Given that change in conductor configuration the resistance is once again calculated using Ohm's law. The new calculated value will be much higher than the original value. To explain why we can use our general formula $R = \rho\,(L/A)$.

In the original conductor in Figure 1.19 the DC current is indicated by a uniform distribution of current flow lines across the conductor cross section. This, of course, is not what actually happens, but serves as a good visual representation for this discussion. The flow lines are all the same length and distributed uniformly over the conductor cross section.

In the reduced cross section conductor a very different flow pattern exists. If the cut to the center is small enough only one of the flow lines can pass along the conductor unimpeded. All the other flow lines must constrict to flow through the single continuous thread of conductor. This is the source of the term constriction resistance to describe this effect.[4]

Now consider the general formula. Recall that the length of all the flow lines but the central one must increase in length in the new configuration. R is directly proportional to L in the general formula which explains the increase in resistance. Alternatively, note that the current flow lines begin to constrict at some distance away from the reduced cross section. This effect can be modeled by taking a number of slices perpendicular to the axis of the conductor and noting that the cross sectional area of each current carrying slice is smaller than the original cross section. R is inversely proportional to A so each of these slices has a higher resistance then the original slice, and all these slices are in series, thus, the increase in resistance.

Note that there is no interface in this model, the conductor is continuous. Constriction resistance is a geometric effect. All contact interfaces will include a number of a-spot

[4] The current flow lines spread out in the other half of the conductor, but the effect on resistance is, of course, the same. In fact, in semiconductor technology this effect is called “spreading resistance”.

interfaces, each of which will introduce a constriction resistance. Thus an interface must produce an increase in resistance to the connector. This resistance can be minimized by maximizing the a-spot contact area, but it cannot be eliminated.

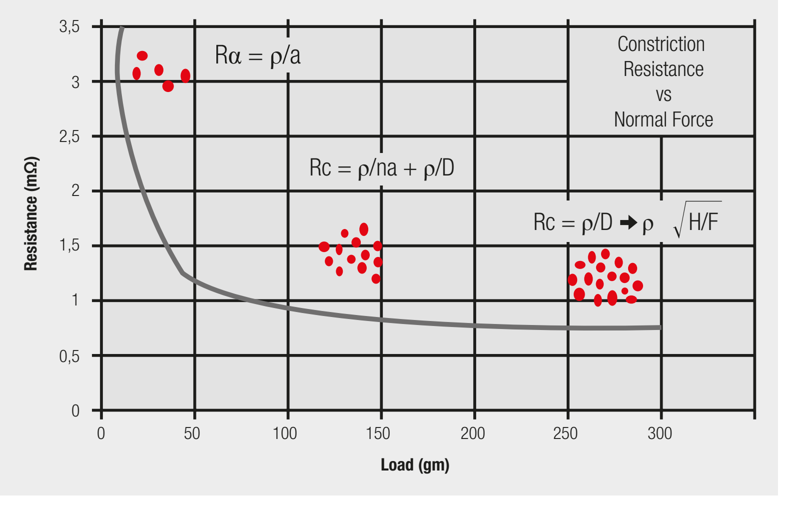


Fig. 1.20: Contact interface resistance vs. contact normal force

The resistance in Figure 1.20 is the constriction resistance, the resistance of the metal-to-metal contact interfaces. As the plug and receptacle surfaces are brought together under the contact normal force, a few asperity contact interfaces form, as illustrated previously in Figure 1.15, such contacts are referred to as a-spots. The resistance of each individual a-spot, R_a, is given by the formula shown in Figure 1.20:

$$R_a = \rho/a_d \tag{1.2}$$

where ρ is the resistivity of the material, and a_d is the **diameter** of the a-spot. As the force is increased and the surfaces deform against one another additional a-spots are created. The second equation now applies:

$$R_c = \rho/na_d + \rho/D \tag{1.3}$$

Where R_c is the contact interface resistance, n is the number of a-spots in parallel and D is the diameter of the apparent contact area, the area over which the a-spots are distributed at the contact interface. These two resistances are in series because the current constricts first to the dimensions of the apparent contact area, defined by D, and then constricts again to flow through the individual a-spots, defined by a_d.

As the contact force continues to increase, the number of a-spots increases along with the apparent contact area. As n increases the a-spot resistance contribution decreases