BONDING

INTRODUCTION

In any realistic electronic system, whether it be only one piece of equipment or an entire facility, numerous interconnections between metallic objects must be made in order to provide electric power, minimize electric shock hazards, provide lightning protection, establish references for electronic signals, etc. Ideally, each of these interconnections should be made so that the mechanical and electrical properties of the path are determined by the connected members and not by the junction. Further, the joint must maintain its properties over an extended period of time in order to prevent progressive degradation of the degree of performance initially established by the interconnection. Bonding is concerned with those techniques and procedures necessary to achieve a mechanically strong, low impedance interconnection between metal objects and to prevent the path thus established from subsequent deterioration through corrosion or mechanical looseness.

In terms of the results to be achieved, bonding is necessary for the [1]:

a. protection of equipment and personnel from the hazards of lightning discharges;
b. establishment of fault current return paths;
c. establishment of homogeneous and stable paths for signal currents;
d. minimization of RF potentials on enclosures and housing;
e. protection of personnel from shock hazards arising from accidental power grounds, and
f. prevention of static charge accumulation.

High noise levels in equipments or systems are frequently traceable to poorly bonded joints in circuit returns and ground planes. The familiar "cold solder joint" is a classical cause of this type of problem. Bonding is also an important element in the performance of EMI interference control measures. For example, adequate bonding of connector shells to equipment enclosures is essential to the maintenance of integrity of cable shields and to the retention of the low loss transmission properties of the cables. The careful bonding of seams and joints in electromagnetic shields is necessary for the achievement of a high degree of shielding effectiveness.

BOND RESISTANCE

A primary requirement for effective bonding is that a low resistance path be established between the two jointed objects. The resistance of this path must remain low with use and with time. The required value of resistance at a particular junction is a function of the current (actual or anticipated) through the path. For example, where the bond serves only to prevent static charge buildup, a very high resistance, i.e., 50 kilohms or higher, is acceptable. However, bonds performing a noise minimization role generally must exhibit a resistance of considerably less than 50 kilohms. Where lightning discharge or heavy fault currents are involved, the path resistance must be even lower yet to minimize heating effects.

A bonding resistance of 1 milliohm can be considered to indicate a high quality junction. Experience shows that 1 milliohm can be reasonably achieved if surfaces are properly cleaned and adequate pressure is maintained between the mating surfaces. A much lower resistance would provide greater protection against very high currents. However, there is little need to strive for a junction resistance that is appreciably less than the intrinsic resistance of the conductors being joined. Higher values of resistance tend to relax the bond preparation and assembly requirements. Such requirements should be adhered to in the interest of long term reliability. Thus, an achievable, yet low, value of 1 milliohm bond resistance ensures that impurities are removed and that sufficient surface contact area is provided to minimize future degradation due to corrosion.

BOND TYPES

Electrical bonds are generally classified as either direct or indirect. A direct bond establishes the desired electrical path between the interconnected members without the use of an auxiliary conductor. Conversely, an indirect bond employs an auxiliary conductor.

Direct Bonds: In a direct bond, specific portions of the surface areas of the members are placed in immediate contact. Properly constructed direct bonds exhibit a low dc resistance and provide an RF impedance as low as the configuration of the bond members will permit. Direct bonding is always preferred; however, it can be used only when the two members can be connected together and can remain so without relative movement.

Direct bonds may be either permanent or semi-permanent in nature. Permanent bonds may be defined as those intended to remain in place for the expected life of the installation and not required to be disassembled for inspection, maintenance, or system modification. Joints which are inaccessible by virtue of their location should be permanently bonded and appropriate steps taken to protect the bond against deterioration.

Permanent bonds are usually realized by establishing a fused metal bridge across the junction by welding, brazing, or soldering. These metal flow processes provide the lowest values of bond resistance. With such processes, the resistance of the joint is determined by the resistivity of the weld or filler metal which usually approaches that of the metals being joined.

Welding: In terms of electrical performance, welding is the ideal method of bonding. The intense heat involved (in excess of 4000° F) is sufficient to boil away contaminating films and foreign substances. The net resistance of the bond is essentially zero because the bridge is very short relative to the length of the bond members. The mechanical strength of the bond is high; the strength of a welded bond can approach or exceed the strength of the bond members themselves. Since no moisture or contaminants can penetrate the weld, bond corrosion is minimized. The errosion rate of the metallic bridge should be comparable to that of the base members; therefore the lifetime of the bond should be as great as that of the bond members. Welds should be utilized whenever practical for permanently joined bonds. Although welding may be a more expensive method of bonding, the reliability of the joint makes it very attractive for bonds which will be inaccessible once construction is completed.

Brazing: Brazing to include silver soldering is also attractive for permanent bonding. In brazing, the bond surfaces are heated to a temperature above 800° F but below the melting point of the bond members. A filler metal with an appropriate flux is applied to the heated members which wets the bond surfaces to provide intimate contact between the brazing solder and the bond surfaces. As with higher temperature welds, the resistance of the brazed joint is essentially zero. However, since brazing frequently involves the use of metal different from the primary bond members, additional precautions must be taken to protect the bond from deterioration through corrosion.

Soft Solder: Soft soldering is frequently used because of the ease with which solder can be applied. Relatively low temperatures are involved and it can be readily employed with several of the high conductivity metals such as copper, tin, and cadmium. With appropriate fluxes, aluminum and other metals can be soldered. Properly applied to compatible materials, the bond provided by solder is nearly as low in resistance as one formed by welding or brazing. Because of its low melting point, however, soft solder should not be used as the primary bonding material where high currents may be present. In addition to its temperature limitation, soft solder exhibits low mechanical strength and tends to crystallize if the bond members move while the solder is cooling. Therefore, soft solder should not be used if the joint must withstand mechanical loading; the tendency toward crystallization must be recognized and proper precautions observed when applying soft solder.

Bolts: Many bonded junctions must retain the capability of being disconnected without destroying or significantly altering the bonded members. Junctions which should not be permanently bonded include those which may be broken for system modifications, for network noise measurements, for resistance measurements, and for other related reasons. In addition, many joints cannot be permanently bonded for reasons of costs. All such connections not permanently joined are defined as semipermanent bonds. Semipermanent bonds include those which utilize bolts, screws, rivets, clamps, and other auxiliary devices for fasteners. The most commonly used semipermanent bond is the bolted connection (or one held in place with machine screws, lag bolts, or other threaded fasteners) because this type bond provides the flexibility and accessibility that is frequently required. The bolt (or screw) should serve only as a fastener to provide the necessary force to maintain the pressure required between the contact surfaces for satisfactory bonding. Except for the fact that metals are generally necessary to provide tensile strength, the fastener does not have to be conductive. Although the bolt or screw threads may provide an auxiliary current path through the bond, the primary current path should be established across the metallic interface. The resistance of bolted (and riveted or clamped) bonds is determined by the nature of the metals involved, the surface conditions within the bond area, the contact pressure at the surfaces, and the cross-sectional area of contact.

No metallic surface is perfectly smooth. In fact, surfaces consist of many peaks and valleys. Even the smoothest commercial surfaces exhibit an RMS roughness of 0.5 to 1 millionth of an inch [2]; the roughness of most electrical bonding surfaces will be several orders of magnitude greater. When two such surfaces are placed in contact, they touch only at the tips of the peaks—called asperities. Theoretically, two infinitely hard surfaces would touch at only three asperities. Typically, however, under pressure elastic deformation and plasticity allows other asperities to come into contact. Current passes between the surfaces only at those points where the asperities have been crushed and deformed [3] to establish true metal contact. The actual areas of electrical contact are equal to the sum of the individual areas of contacting asperities. This actual area of contact can be as little as one millionth of the apparent (gross surface) contact area [4].

The true contact area will be reduced further by any impurities. Foreign particulate matter on the bond surfaces will impair bonding. Dirt and other solid matter such as high resistance metal particles or residue from abrasives can act as stops to prevent metallic contact. The surface films that are present on practically every bond surface will also resist contact. If the surface films are much softer than the contact material, they can be squeezed from between the asperities to establish a quasimetallic contact. Harder films, however, may support all or part of the applied load, thus reducing or eliminating the conductive contact area.

The hardness of the bond surfaces also affects the contact resistance. Under a given load, the asperities of softer metals will undergo greater plastic deformation and establish greater metallic contact. Likewise, at a junction between a soft and a hard material, the softer material will tend to conform to the surface contours of the harder metal and will provide a lower resistance contact that would be afforded by two hard materials. Table 1 shows how the resistance of a 1 square inch (6.45 square cm) test bond varied with the type of metals being joined.

The variation of resistance of a 1 square inch bond is shown in Figure 1 as a function of the torque applied to the fastener. The resistance variation for brass is lowest due to its relative softness and the absence of insulating oxide films. Even though aluminum is relatively soft, the insulating properties of aluminum oxide cause the bond resistance to be highly dependent upon fastener torque up to approximately 40 in-lb torque (which corresponds to a contact pressure of about 1200 psi). Steel, being harder and also susceptible to oxide formations, exhibits a resistance that is dependent upon load below 80 in-lb or about 1500 psi (for mild steel). Above these pressures, no significant lowering of contact resistance is evident.

Bond areas as large as practical are desirable. Large surface areas maximize the cross-sectional area of the path for current and correspondingly maximizes the total number of true metallic contacts between the surfaces. In addition to the obvious advantage of decreased bond resistance, the current crowding which can occur during power fault conditions or under a severe lightning discharge is lessened. A further advantage of a large area bond is that it will be mechanically stronger and will be less susceptible to long term corrosion because a smaller portion of the total bond area is exposed to the environment.

The size, number, and spacing of the fasteners should be sufficient to establish the required bonding pressure over the entire joint area. The pressure exerted by a bolt is concentrated in the immediate vicinity of the bolt head. However, large, stiff washers can be placed under the bolt head to increase the effective contact area. Because the load is distributed over a larger area, the tensile load on the bolt should be raised by increasing the torque. Appropriate nomographs [6] may be used to calculate the necessary torque for the size bolts to be used. Where the area of the mating surfaces is so large that unreasonably high bolt torques are required, more than one bolt should be used. For very large mating areas, rigid backing plates should be used to distribute the force of the bolts over the entire area.

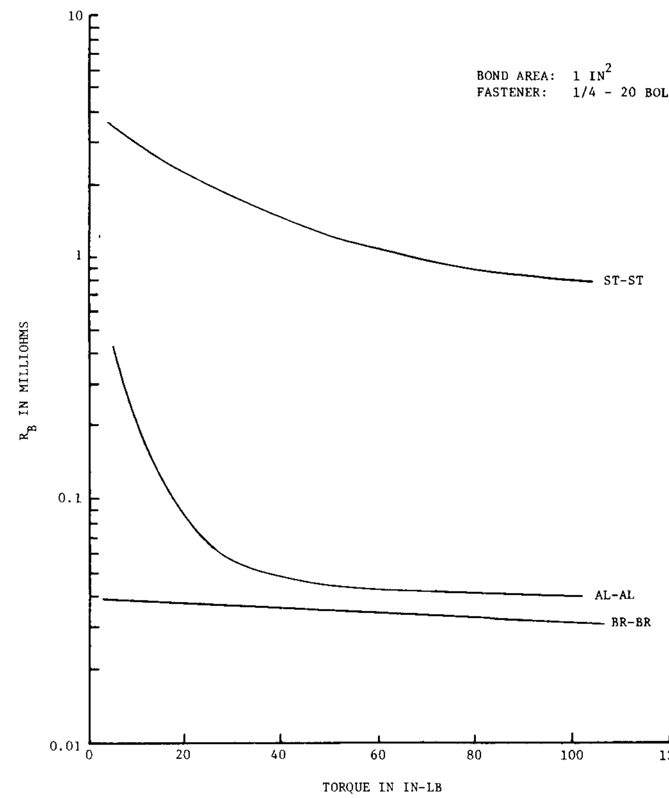

Figure 1. Bond Resistance Variation as a Function of Fastener Torque [5].

Table 1

Resistance of Direct Bonds Between Selected Metals [5]

Bond Composition	Resistance (Micro-ohms)
Brass-Brass	6
Aluminum-Aluminum	25
Brass-Aluminum	50
Brass-Steel	150
Aluminum-Steel	300
Steel-Steel	1500
Notes: Apparent Bond Areas: 1 in² Fastener Torque: 100 in-lb	

Indirect Bonds: In spite of the obvious advantages of a direct bond, operational requirements or equipment locations often preclude direct bonding. When physical separation is necessary between the elements of an equipment complex or between the complex and its reference plane, auxiliary conductors must be incorporated as bonding straps or jumpers. For example, straps are commonly used for the bonding of shock mounted equipment to the structural ground reference. Bond straps are also used to prevent static charge buildup and to connect metal objects to lightning down conductors to prevent flashover.

The resistance of an indirect bond is equal to the sum of the intrinsic resistance of the bonding conductor and the resistance of the metal-to-metal contacts at each end. The resistance of the strap is determined by the resistivity of the material used and the dimensions of the strap. With typical straps, the dc bond resistance is small. For example, with a resistivity of 6.77 x 10^{-7} ohm-inches (1.72 x 10^{-6} ohm-cm), a copper conductor 1 inch wide, 40 mils thick, and 1 foot long has a resistance of 0.2 milliohms. To this resistance will be added the sum of the dc resistances of the direct bonds at the ends of the strap. With aluminum, copper, or brass straps, these resistances should be less than 0.1 milliohm with properly made connections. However, a low dc bond resistance is not a reliable indicator of the performance of the bond at higher frequencies. Inherent conductor inductance and strap capacitance, along with the associated standing wave effects and path resonances, will determine the impedance of the bond. Thus, in RF bonds, these factors must be considered along with the dc resistance.

Strap Inductance: The geometric configuration of the bonding conductor and the physical relationship between objects being bonded introduce reactive components into the impedance of the bond. The strap itself exhibits an inductance that is related to its dimensions. Even at relatively low frequencies, the reactance of the inductive component of the bond impedance becomes much larger than the resistance [5], [7]. Thus, in the application of bonding straps, the inductive properties as well as the resistance of the strap must be considered. As the length, **ℓ**, of the strap is increased, its impedance increases nonlinearly for a given width; however, as the width, **b**, increases, there is a nonlinear decrease in strap impedance. The relative reactance of a strap decreases significantly as the length to width (**ℓ/b**) ratio decreases [8]. Because of this reduction in reactance, bonding straps which are expected to provide a path for RF currents are frequently recommended to maintain a length-to-width ratio of 5 to 1 or less, with a ratio of 3 to 1 preferred.

Capacitance Effects: A certain amount of stray capacitance is always present between the bonding jumper and the objects being bonded and between the bonded objects themselves. Figure 2 shows an equivalent circuit for the bonding strap alone. R_s represents the resistance of the strap,, is the inductance, and C_s is the stray capacitance between the jumper and the two members being bonded. Except for extremely short straps, the magnitude of the inductive reactance of the strap will be significantly larger than the resistance and, at frequencies above approximately 100 kHz, the R_s term can be ignored. Thus, not considering R_s, the equation for the impedance Z_s, of the equivalent circuit is

$$|Z_s| = \frac{\omega L_s}{1-\omega^2 L_s C_s}$$

The equivalent circuit of Figure 2 does not take into account the effects of the equipment enclosure or other object being bonded. Figure 3, however, shows the true equivalent circuit of an indirectly bonded system. The bonding strap parameters are again represented by R_s, C_s, and L_s. The inherent inductance of a bonded object, e.g., an equipment rack or cabinet, is represented by L_c and the capacitance between the bonded members, i.e., between the equipment and its reference plane, is represented by C_c. In most situations, $L_s >> L_c$, $C_c >> C_s$, and R_s can again be ignored. Thus, the primary (i.e., the lowest) resonant frequency is given by

$$f_r = \frac{1}{2\pi\sqrt{L_s C_s}}$$

These resonances can occur at surprisingly low frequencies--as low as 10 to 15 MHz [5] in typical configurations. In the vicinity of these resonances, bonding path impedances of several hundred ohms are common. Because of such high impedances, the strap is not effective. In fact, in these high impedance regions, the bonded system may act as an effective antenna system which increases the pickup of the same signals which bond straps are intended to reduce. Figures 4 and 5 show the measured effectiveness of two different lengths of bonding straps in the reduction of the voltage induced by a radiated field on an equipment cabinet above a

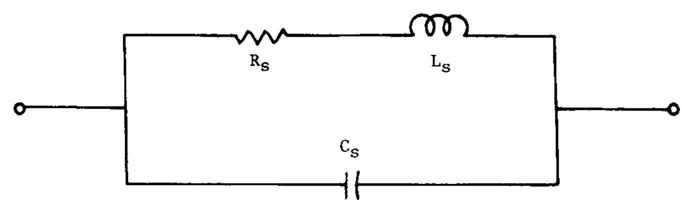

Figure 2. Equivalent Circuit for Bonding Strap.

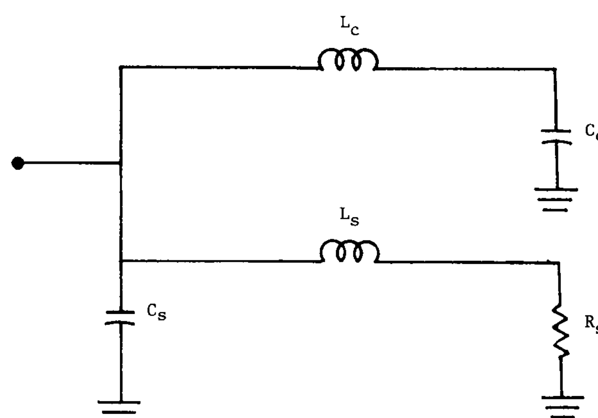

Figure 3. True Equivalent Circuit of a Bonded System.

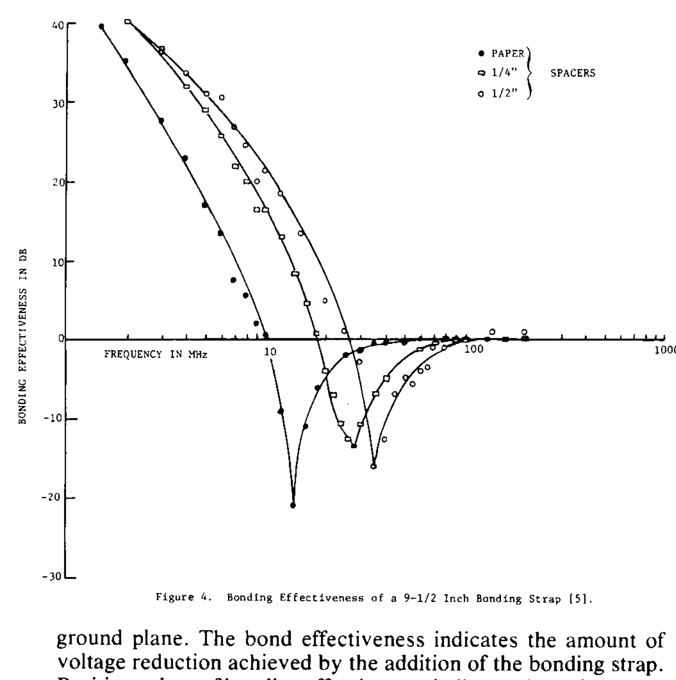

Figure 4. Bonding Effectiveness of a 9-1/2 Inch Bonding Strap [5].

ground plane. The bond effectiveness indicates the amount of voltage reduction achieved by the addition of the bonding strap. Positive values of bonding effectiveness indicate a lowering of the induced voltage. At frequencies near the network resonances, the induced voltages are higher with the bonding straps than without the bonding straps. These figures show that:

a. at low frequencies where the reactance of the strap is low, bonding straps will provide effective bonding;
b. at frequencies where parallel resonances exist in the bonding network, straps may severely enhance the pickup of unwanted signals; and
c. above the parallel resonant frequency, bonding straps do not contribute to the pickup of radiated signals either positively or negatively.

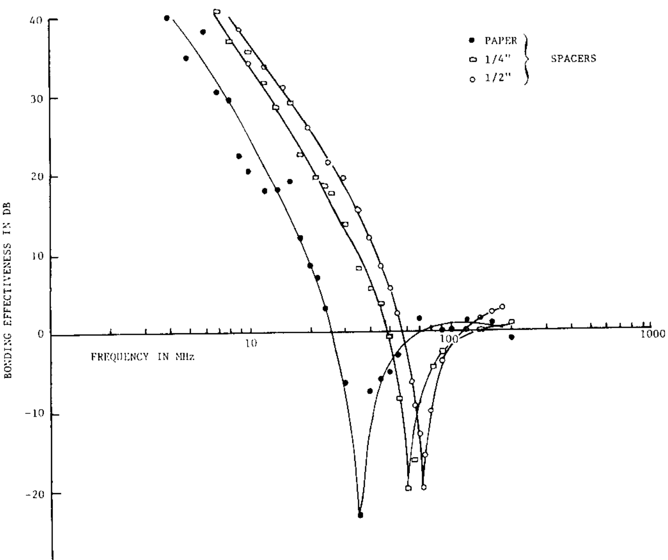

Figure 5. Bonding Effectiveness of a 2-3/8 Inch Bonding Strap [5].

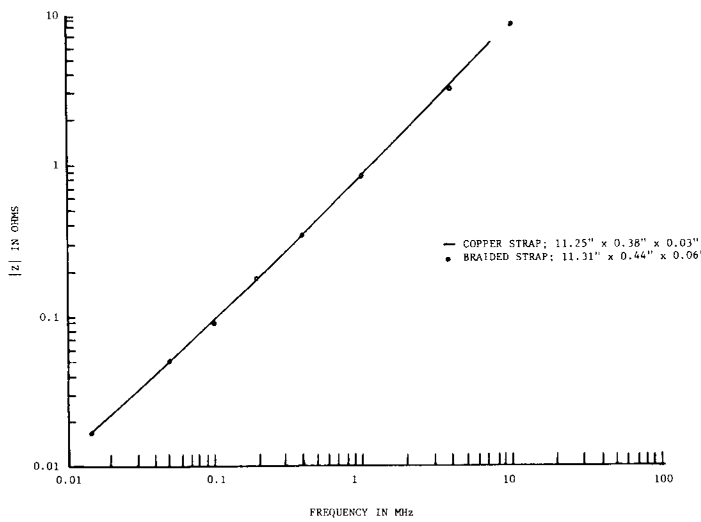

Figure 6. Frequency Variation of the Impedance of Simple Conductors [5].

Braided Straps: In many applications, braided straps are preferred over solid straps because they offer greater flexibility. Figure 6 compares the measured impedance properties of a braided copper strap with those of a solid copper strap and shows that no significant difference exists between the impedance of the braided or solid strap. Other tests [7] confirm that there is no essential difference in the RF impedance properties of braided and solid straps of the same dimensions and made of the same materials. Because the strands are exposed they are more susceptible to corrosion; thus braided straps may be undesirable for use in some locations for this reason.

BOND ASSEMBLY AND CORROSION PROTECTION

To achieve an effective and reliable bond, the mating surfaces must be free of any foreign materials, e.g., dirt, filings, preservatives, etc., and nonconducting films such as paint, anodizing, and oxides and other metallic films. Various mechanical and chemical means can be used to remove the different substances which may be present on the bond surfaces. After cleaning, the bond should be assembled or joined as soon as possible to minimize recontamination of the surfaces. After completion of the joining process, the bond region should be sealed with appropriate protective agents to prevent bond deterioration through corrosion of the mating surfaces.

Corrosion is the deterioration of a substance (usually a metal) because of a reaction with its environment. Most environments are corrosive to some degree. Those containing salt sprays and industrial contaminants are particularly destructive. The requirements for corrosion to take place are that (1) an anode and cathode must be present to form an electrochemical cell and (2) a complete path for the flow of direct current must exist. Anything that prevents the existence of either of these conditions will prevent corrosion. For example, paint will keep moisture from reaching the bond members and thus prevent the necessary electrolytic path from being established.

The oxidation of metal involves the transfer of electrons from the metal to the oxidizing agent. In this process of oxidation, an electromotive form (EMF) is established between the metal and the solution containing the oxidizing agent. A metal in contact with an oxidizing solution containing its own metal ions establishes a fixed potential difference with respect to every other metal in the same condition. The set of potentials determined under a standardized set of conditions, including temperature and ion concentration in the solution, is known as the EMF (or electrochemical) series [9]. The importance of the EMF series is that it shows the relative tendencies of metals to corrode. Metals high in the series react more readily and are thus more prone to corrosion. The series also indicates the magnitude of the potential established when two metals are coupled to form a cell. The farther apart the metals are in the series, the higher the voltage between them. The metal higher in the series will act as the anode and the one lower will act as the cathode. When the two metals are in contact, loss of metal at the anode will occur through oxidation to supply the electrons to support current flow. This type of corrosion is defined as galvanic corrosion. The greater the potential difference of the cell, i.e., the greater the dissimilarity of the metals, the greater the rate of corrosion of the anode.

When joints between dissimilar metals are unavoidable, the anodic member of the pair should be the largest of the two. For a given current flow in a galvanic cell, the current density is greater for a small electrode than for a larger one. The greater the current density of the current leaving an anode, the greater is the rate of corrosion. As an example, if a copper strap or cable is bonded to a steel column, the rate of corrosion of the steel will be low because of the large anodic area. On the other hand, a steel strap or bolt fastener in contact with a copper plate will corrode rapidly because of the relatively small area of the anode of the cell.

The EMF series is based on metals in their pure state--free of oxides and other films--in contact with a standardized solution. Of greater interest in practice, however, is the relative ranking of metals in a typical environment with the effects of surface films included. This ranking is referred to as the galvanic series. The most commonly referenced galvanic series is listed in Table 2. This series is based on tests performed in sea water and should be used only as an indicator of possible corrosion problems where other environments are of concern.

Table 2

Galvanic Series of Common Metals and Alloys in Seawater

(ANODIC OR ACTIVE END)
Magnesium
Magnesium Alloys
Zinc
Galvanized Steel or Iron
1100 Aluminum
Cadminum
2024 Aluminum
Mid Steel or Wrought Iron
Cast Iron
Chromium Steel (active)
Ni-Resist (high-Ni cast iron)
18-8 Stainless Steel (active)
18-8 Mo. Stainless Steel (active)
Lead-tin Solders
Lead
Tin
Nickel (active)
Inconel (active)
Hastelloy B
Manganese Bronze
Brasses
Aluminum Bronze
Copper
Silicon Bronze
Monel
Silver Solder
Nickel
Inconel
Chromium Steel
18-8 Stainless Steel
18-8 Mo. Stainless Steel
Hastelloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum
(CATHODIC OR MOST NOBLE END)

SUMMARY GUIDELINES

The effectiveness of the bond depends upon its construction, the frequency and magnitude of the currents flowing through it, and the environmental conditions to which it is subjected. To ensure maximum bond effectiveness, the following guidelines are suggested:

a. Bonds must be designed into the system. Specific attention should be directed to the interconnections not only in power lines and signal lines, but also between conductors of signal ground bus networks, between equipments and the ground bus networks, between both cable and component or compartment shields and the ground reference plane, between structural members, and between elements of the lightning protection network. In the design and construction of a facility, signal path, personnel safety, and lightning protection bonding requirements must be considered along with mechanical and operational needs.

b. Bonding must achieve and maintain intimate contact between metal surfaces. The surfaces must be smooth and clean and free of non-conductive finishes. Fasteners must exert sufficient pressure to hold the surfaces in contact in the presence of the deforming stresses, shocks, and vibrations associated with the equipment and its environment.

c. Bonding jumpers are only a substitute for direct bonds. If the jumpers are kept as short as possible, have a low resistance and low ℓ/w ratio, and are not higher in the electrochemical series than the bonded members, they can be considered a reasonable substitute.

d. Bonds are always best made by joining similar metals. If this is not possible, special attention must be paid to the control of bond corrosion through the choice of the materials to be bonded, through the selection of supplementary components (such as washers) to assure that corrosion will affect replaceable elements only, and through the use of protective finishes.

e. The bond surfaces must be kept free of moisture before assembly and the completed bond must be sealed against the entrance of moisture into the mating region. Acceptable sealants are paint, silicone rubber, grease, and polysulfates. Where paint has been removed prior to bonding, the completed bond should be repainted to match the original finish. Excessively thinned paint should be avoided; otherwise, the paint may seep under the edges of the bonded components and impair the quality of the connection.

f. Finally, throughout the lifetime of the equipment, system, or facility, the bonds must be inspected, tested, and maintained to assure that they continue to perform as required.

REFERENCES

[1] "Bonding, Electrical and Lightning Protection, for Aerospace Systems," Military Specification MIL-B-5087B(ASG), 15 October 1964.

[2] D. D. Fuller, Theory and Practice of Lubrication for Engineers, Wiley, New York, N.Y. (1956)

[3] J. C. Bailey, "Bolted Connections in Aluminum Busbars," The Engineer, Vol. 199, pp. 551-554, April 22, 1955.

[4] L. Jedynak, "Where the (Switch) Action Is," IEEE Spectrum, October 1973, pp. 56-62.

[5] H. W. Denny and W. B. Warren, "RF Bonding Impedance Study," RADC-TR-67-106, Contract AF30(602)-3282, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, GA, March 1967.

[6] "Nomogram for Torque on Bolts," Design News, May 22, 1972.

[7] R. W. Evans, "Metal-to-Metal Bonding for Transfer of Radio Frequency Energy," IN-R-ASTR-64-15, NASA Marshall Space FLIGHT Center, Huntsville, AL, June 25, 1964.

[8] R. J. Troup and W. C. Grubbs, "A Special Research Paper on Electrical Properties of a Flat Thin Conductive Strap for Electrical Bonding," Proceedings of the Tenth Tri-Service Conference on Electromagnetic Compatibility, IITRI, Chicago, IL, November 1964, pp. 450-474.

[9] American Institute of Physics Handbook, Second Edition (1963).

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