“Contacts in Motion”

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> *‘..it is necessary to know the nature of the contact which this weight has with the smooth surface where it produces friction by its movement..’*
>
> LEONARDO DA VINCI

Abstract

This paper discusses the role of motion at the electrical contact interface in how contacts work and in how they fail. After first noting some trends in the connector industry and their consequences for the design of connectors the principal failure modes are described insofar they are related to motion. These are illustrated by an analogy between the contact area and motion at the contact interface and the behaviour of a geological landscape. Four causes of motion are discussed. It is concluded that control of motion at the interface is the most effective way to improve the reliability of electrical connectors.

1. Introduction

Leonardo da Vinci wrote that it is necessary to understand the nature of motion and friction, yet he probably did not have electrical contacts in mind. In this paper I will try to explain why it is also necessary to understand the causes and effects of motion on the interface of electrical contacts.

The present trend in the industry is to use connectors with more and smaller contacts, lower normalforces[1], high data rates, low currents and voltages and last but not least lower prices. Higher pin counts and smaller centerlines cause a tendency to fix contacts more rigidly in housings. In the past it was common that at least one mating half of a connection was not fixed in the housing so that the contacts could align on each other, were free to move together, and were not affected by motion passed on by housings. Fixing both parts to separate subassemblies invites motion to occur in several ways other than just by insertion and withdrawal. Such ways can be because of a lack of mechanical robustness either statically or dynamically, or because of differences in thermal expansion. I will discuss these ways in more detail later.

In the past big companies had internal connector laboratories with experts who served as watchdogs for the reliability of connections.

Those companies made rules, based on their own research and experience. An example of a rule from the telecommunications industries is that 1 N normalforce, a good wiping motion and redundancy by two independent contacts are prerequisites for almost zero fault levels with gold plated contacts.

Over the past period we have seen that many of the big companies closed their internal laboratories and made it their policy to rely on connector suppliers, their know-how and ability to provide products with zero defects. The watchdogs are gone.

Today there are applications with gold plated contacts where there is no redundancy and where normalforces are reduced to 0.25 N with the intent of lessening wear and where the contacts are exposed to dust and other contaminants as well, thus completely contrary to the original rules.

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[1] normalforce is spelled as one word to distinguish it from normal force, which could be interpreted wrongly.

Also we come across situations where a contact spring of good design will not give a reliable connection, just because of a lack of rigidity in the connection system as a whole, leading to relative motion at the contact interface. Applications tend to become less forgiving for electrical reasons as well, for example high data rates are sensitive to intermittence due to occurrences at the connector interface, also sensors are more sensitive to small voltage fluctuations.

Not every application is critical however. If the voltage is high enough the electrical field will be strong enough to form a conductive path by fritting. If the electrical circuit has enough inductance it will not be sensitive to short interruptions. The dependence of connector reliability on so many different parameters means that it is reckless to make a general statement that a certain connector is reliable. Reliability is an attribute that depends on the connector and on its application. It is important that responsible designers and purchasing people are well aware of possible risks of failure, however difficult it is to quantify these risks. **Therefore the involvement of connector designers in an early stage of system design is a must**.

2. Connectors

Connectors are electromechanical systems that are designed to enable connection and disconnection, normally by insertion and withdrawal. The requirement for connectors is that their influence on the function of the electrical circuit must be small enough to be acceptable.

When clean metal contacts are pressed together they transmit electrical current very well, even under loads lower than one Newton. Problems arise when contact surfaces become contaminated by substances such as oxides, salts, moisture and organic matter, and particularly once they move relative to each other.

2.1 How contacts work

Gold and tin are the most used top layers in surface finish systems for electrical contacts.

Gold is used because of its unique nobility, enabling the use of normalforces of 1 N and lower in connector contacts. Gold surfaces are supposed to be relatively clean and to remain gold, consequently they are sensitive to contamination and to wear-through. The challenge is to have enough force and the proper geometry to penetrate through the contamination layers, yet not so much force (at a given geometry) that wear-through occurs. With hard gold plated contacts a number of 1000-10,000 mating cycles is possible before wear through takes place.

Tin is a very soft metal. It is protected by a very hard and brittle oxide-layer, quickly formed and always present on top of the soft tin layer. This combination of thin hard oxide on a soft substrate makes it attractive as a contact finish. With forces of 1-3 N the thin oxide layer is easily broken and a large conductive area is generated between the surfaces to be connected. Of course these forces causes deformation and wear in the process of breaking the oxide layer repeatedly over large areas, so that the number of mating cycles is bound to be limited to 10-100.

For gold plated as well as for tin plated contacts it is important to find a good combination of contact material, contact geometry and a contact spring that is stiff enough to provide mechanical stability, and also resilient enough to limit the normalforce range. This normalforce range depends on tolerances of the spring and pin dimensions and of the alignment. Insertion forces will have a wider force range, because of the extra tolerances on the lead-in geometry and the variability of the coëfficient of friction.

2.2 How contacts fail

The major failure mechanisms for gold and for tin plated contacts are very different in appearance. Gold plated contacts will fail mostly by contamination, pore corrosion, corrosion creep and/or wear-through in the contact area.

With tin-plated contacts the major cause of problems is fretting corrosion, whereby the combination of cyclic motion and oxidation forms a very much localised corrosion spot.

Despite the difference in appearance between the failure mechanisms for gold and for tin, the underlying mechanism for failure is in both cases related to sliding motion at the contact interface. Motion causes wear and deformation, it creates reactive surface and it pushes contaminants to and from the contact area.

This is why it is important to understand the effects that motion has on the interface and the possible causes of motion. Paragraph 3 will deal with the effect of motion on contact interfaces and paragraph 4 with the different causes of motion.

3. Interfaces in motion

The earliest known descriptions of friction at the interface are from Leonardo da Vinci (1452-1519) and from the French scientists Mantonson (1699) and Coulomb (1781). To their surprise they found that the friction force depends on normalforce and coëfficient of friction only, not on apparent area or geometry. They were also surprised that the coëfficient of friction is very similar for most metals, and found it to be very dependent on surface contamination like with oxides, moisture and organics.

In the middle of this century Bowden and Tabor in 'The Friction and Lubrication of Solids' [1] [2] presented the modern understanding of friction, while HOLM in his famous book 'Electric Contacts' [3] discusses electrical contacts more in particular. They depict contact surfaces as a collection of individual spots (so-called contact asperities or a-spots) that transmit the current from one surface to the other. Williamson in his paper 'The Microworld of the Contact Spot' [3] makes it more imaginable by comparing it to placing Vermont upside down on New Hampshire. Also the Nürnberg neighbourhood lends itself to such visualisation. At a hundred million times magnification 1x1 mm transforms to 100x100 km. A 1 μm thick plating layer, consisting of metal atoms, on a surface with a roughness of 0.5 μm transforms to a 100 meters thick layer of golf balls on top of 50 meters high hills. Pressing a hemispherical surface with a radius of 1mm and a flat surface together with a normalforce of 1 N generates a contact area of about 40x40 μm or 4x4 km. Not all of this area is in electrical contact; it is just the general area in which many hills touch, forming a real area of mechanical contact of about 8 km^2. The proportion of electrically conductive area depends still on the amount and nature of oxides and organic matter on the surface. My contribution today is to add motion to this picture. Let us look at a slow sliding speed of 1mm/min like in a piece of test equipment. If one magnifies this speed with the same factor 10^8 you have to imagine standing in a valley and looking up to a moving hemispherical counterpart that passes at a height of about 25 meters with a speed of 6000 km/hr. It will cause the ground underneath you to be depressed by 50 meters while the 4 km spot passes by in about 2.5 s. It is easy to imagine that such movement plays an important role in the formation of a much larger contact surface than normalforce alone would generate. On the microscale the sliding motion causes a lot of deformation and wear, it has a strong cleaning effect as well.

In many investigations on contact materials the contact resistance is measured without applying a wiping motion. Although this is fine for the detection of surface films, it does not say much about how materials will behave as a contact material after a wiping motion. Also in some papers true surface area is estimated and contact resistance calculated as if there were no wiping motion. It is generally known from field experience that even gold plated contacts need a wiping motion in order to be reliable. The effect of the wiping distance, normalforce and geometry is discussed in papers by Brockman, Sieber and Mroczkowski [4], the effect of lubricants on the wiping motion in a paper by myself [5].

4. Causes of motion

The previous paragraph depicted motion at the interface and its effect on electrical contacts. An important issue is whether it is possible to prevent motion at the interface. Some papers suggest that some motion will always take place at interfaces. This is a theoretically true statement, particularly if thermal expansion is considered. However some motion does not mean gross slip, it may be either partial slip or a small rocking or wiping motion or both. We know cases where connectors function properly at one place in a piece of equipment and fail at another place in the same piece of equipment: there was no slip at the interface at one place while it did occur at the other place. Papers by van Meijl and myself [7] [8] and by Kassman Rudolphi and Jacobson [9] compare situations with gross slip to situations where the construction is improved and gross slip prevented. In both cases stable electrical behaviour could be achieved.

It follows that a more detailed analysis of causes of motion is important.

Four causes of motion are distinguished and will be discussed below.

4.1 **The sliding motion during insertion/withdrawal**.

This motion is directly associated with the function of the connection and is the only motion at the electric contact interface that is intentional. It is studied in many papers. An important consideration is the trade-off between on one hand high force and sharp geometry to penetrate through non-conductive surface films and on the other hand low force and round geometry to limit wear. Testing by insertion/withdrawal cycling is included in test and product specifications. There are several problem areas. One is that such tests do not reproduce well (due to different surface conditions). Further that the samples are not always representative (process changes, tolerances). Also there is a difference between mating by hand and mating by machine. Further there is a fundamental difficulty in relating a test sequence with a number of matings followed by a gas or humidity/temperature exposure and a resistance measurement to a field condition where the mating cycles and environmental exposures take place in a more random order.

Wear and the effect of underplate and substrate and lubrication are investigated and discussed in papers by Antler [10] and by Antler and Drozdowicz [11]. Tangena [12] has undertaken an effort to approach this with a finite element model, an approach also advocated by Fluss [13] and certainly worthwhile as it can generate a more detailed understanding of the wear process.

4.2 **Interfacial motion caused by play or low stiffness in the connection system**.

In hand-held devices, for example, battery connections are often mounted with play using springs that are soft in relation to the mass of the battery. These masses will under conditions of shock or external force changes move over distances of 0.1 mm or more. The number of cycles is very dependent on the application, but can easily be 10 per day. This adds up to 15.000 cycles over a 5-year life cycle, more than you would specify as a number of insertion cycles.

4.3 **Interfacial motion due to differences in thermal expansion**.

If there is no play and if part of the construction is of plastic material and another part of a metal relative motion can very well take place at the contact interface. This can either be due to the difference in coëfficient of thermal expansion or to temperature differences between parts of the construction. Long card edge connectors and IC-sockets are examples where such phenomena occur. Cable connectors where the insulation of wires is glued to the housings are another example. The number of cycles depends on the application, but anywhere from 10.000 to 100.000 for a life cycle of a product is likely.

4.4 **Interfacial motion caused by vibration in racks, cable and connection systems**.

From transportation by truck or train of large printed circuit boards mounted in a rack and connected with edge or two-piece connectors it is known that they sometimes arrive with worn-through contacts. Also the design of connections to vibrating car and truck engines requires extreme care to avoid problems of relative motion and fretting corrosion. The number of fretting cycles will be exceedingly large if relative motion takes place: 36.000-180.000 per hour with frequencies like 10-50 Hz!

An EEC subsidised Brite/EuRam project group with European connector users, connector manufacturers and universities (ELECON) performs a study titled "Functionality of electrical contacts subjected to mechanical vibrations". The major issue is how much motion is allowable under circumstances of vibration and how this motion or its effect can be reduced.

5. Summary and Conclusions

I have been asking myself numerous times the following question: “Can contacts be expected to survive large numbers of motion cycles under power, considering that they survive with difficulty 10-1000 insertion cycles without being powered?” Previously several authors have stressed how decisive the role of motion is for the reliability of connection systems.
Abbott concludes in his paper “Materials, Environment, Motion, and Electrical Contact Failure Mechanisms” [14]: ‘For the purpose of this paper, it is important to note that two key ingredients were present. These are films and motion.’ And next: ‘in the absence of motion, there was no detectable change in contact resistance on any system to within 0.1 milliohm.’

Considering the issues discussed in this paper my conclusions are as follows:

1. **It is important to investigate how much motion (slip, rocking) can be allowed at the contact interface without compromising the electrical performance.**
2. **It is a challenge for system designers and connector designers to invent constructions that limit motion other than the motion of the insertion and withdrawal.**
3. **For the design of reliable connection systems it is a must to involve connector designers in an early stage of system design.**

6. References

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