Critical Reliability Aspects of Electrical Contacts

Piet van Dijk
PVDIJK BV Consultancy, The Netherlands
E-mail: pvdijk@pvdijk.com

Abstract— **The key for achieving reliable electrical contacts is to ensure a predictable, reproducible and satisfactory field performance over the whole lifetime of the application. There are many aspects of physical and mechanical nature that need to be considered in the design and manufacturing processes as well as in the interpretation of research and test results.**
Previous research demonstrates that the results of experiments with a specific set of parameters like normalforce, Hertz stress, wiping motion, choice and thickness of materials, temperature, voltage, current and frequency cannot be transferred directly to other combinations of variables. No exact limits exist for these factors. The validity of the results of general research experiments is therefore limited and the experiments and the interpretation of the results are complex.
Reliability figures like MTTF and PPM do not apply. Instead a basic understanding of the underlying physical phenomena is required; therefore application related testing of the assemblies that contain the electrical contacts is a must to establish the reliability.
In this paper analogies of the contact area will be presented to promote the understanding from the electrical contact behaviour, also the most relevant aspects of connector reliability will be discussed.

***Index Terms*—Electrical Contacts, Reliability, Normalforce, Hertz stress.**

1. Introduction

It is very costly when a piece of equipment a car, a computer or a telephone fails because of failing electrical contacts. In order to avoid such failure it is necessary to have a good basic understanding of the physics and mechanics of electrical contacts and the properties of the applied materials. This basic understanding is not only essential for connector users and their suppliers, but also for equipment system design engineers. Often cheaper and better contact systems are possible when considering the contact design in an early stage of system design.

The intention of this paper is to discuss the major factors and basic theory involved in the reliability of contact systems. Next chapters discuss the parameters that influence the reliability of electrical contact systems, the contact physics and mechanics and the contact materials.

2. Contact Reliability

2.1. General

Reliability can be defined as the probability that a contact system will perform as specified for a defined lifetime under given environmental and mechanical stresses [1].

It is not straight-forward how to establish the reliability of a specific contact, particularly not when multi-contact connector systems are concerned. The reason is that the contact or connector system mostly is an integral part of a piece of equipment that has effect on its physical/mechanical behaviour, while also the electrical requirements can vary strongly between different applications. For example a 220 V wire to wire connection carrying only 2 Amp is not critical at all, while a 2 V connection in a high frequency, low force multi-pole board to board connector for the telecom market will need gold plated contacts and a well defined product design and an accurately controlled manufacturing process.

2.2. Contact parameters

The major parameters that influence the reliability of contact systems are as follows:

a. The general contact design.

This relates to the shape of the individual contact partners and the number of parallel contacts. When a contact has a failure rate of 1000 ppm, then placing two independent contacts in parallel will reduce the failure rate to 1 ppm!

b. The normalforce.*

This is the most important parameter in ensuring that a good electrical contact will be established.

The stress relaxation of the spring must be low enough to ensure that the normalforce is maintained at an acceptable level for the lifetime of the contact.

c. The electrical parameters: V, I and frequency.

At higher voltages (> 50 V) the phenomenon of fritting will cause conduction through insulating films [2], making the contact less sensitive to insulating layers. Hence at low voltage reliability is more critical.

For high currents the contact and constriction resistances need to be low to avoid overheating of the contact point.

---

*normalforce = force perpendicular to the surface, is written as one word to avoid confusion with a normal force = force as one would expect

High currents can also improve a contact by softening the material in the contact spot but when it comes to welding it will cause extreme wear and thereby compromise the achievable number of mating cycles.
At high frequencies (>1 GHz) the signal integrity and the absence of short interruptions are of concern. Also contacts for shielding and grounding, for example in coax connections, become increasingly critical and do no longer allow resistive, capacitive or unstable connections, also not for grounds and shields.

d. Wear.

The number of mating cycles should not deteriorate the contact to a degree that the reliability becomes compromised.
Shock, vibration and difference in thermal expansion can cause motion between interfaces that will also result in wear or even fretting wear.

e. The environmental parameters.

The temperature and temperature changes in the application can have a strong effect on the contact reliability. Stress relaxation, diffusion and corrosion are temperature related. Also the humidity, changes of humidity and the presence of pollutants and dust particles in the atmosphere can have a strong effect [3].

2.3. MTTF and PPM figures.

The reliability figures such as MMTF (Mean Time To Failure) and PPM (defect Parts Per Million) are defined for applications where a test under normalized conditions can be done. However these methodologies are not meaningful for contact systems that are used in various applications with different electrical, mechanical and/or environmental parameters.

2.4. The POF (Physics of Failure) approach.

Several authors [1] [4] introduce the POF method, which requires the identification of potential failure modes and the development of a test program to predict the reliability for each specific application. This is generally the best approach used to establish the reliability of electrical contact systems.

3. Contact Physics and analogies

Contact surfaces are depicted as a collection of small spots (so-called contact asperities or a-spots) where the current is transmitted from one surface to the other [5]. Fig. 1 shows a picture from an area of 80x80 µm of a metal surface made by atomic force microscopy [6]. The upper picture at the left shows the roughness of a typical rolled connector material surface. Peaks are about 1 µm high. The vertical scale is more magnified than the horizontal scale, as usual in roughness measurements, therefore one of the peaks is shown in true proportion in the under left picture. The upper right picture shows the remaining plastic deformation of the surface after release of the force. The picture under at the right shows the ground plane of the deformed surface peaks, which is comparable to how a collection of a-spots would look like. An analogy can be made between such a contact surface and a geological landscape by trying to imagine a contact surface at hundred million times magnification [7]. Then a surface area of 1x1 mm transforms to 100x100 km. A 1 µm thick coating on such a surface with height differences of 1 µm transforms to a 100 meters thick layer, a stack of 4000 layers of golf balls, on top of 100 meters high hills.

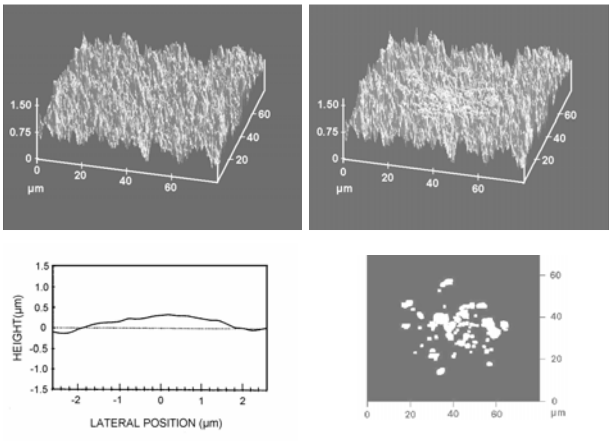
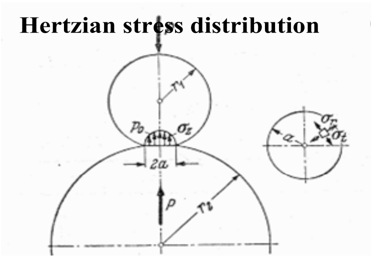


Fig. 1. Surface roughness measured over a 80x80 µm area by Atomic Force Microscopy before and after application of a 1N normalforce on a gold plated surface (upper pictures), roughness in realistic proportion and ground plane of the deformed peaks (lower pictures). (Source: Wake Forest University)

A contact area of about 40x40 µm magnified becomes about 4x4 km. Not all of this area is in electrical contact; it is just the general area in which hill tops touch, forming a much smaller real area of mechanical contact, depending primarily on the normalforce and the hardness of the surface layer. The electrically conductive area can be even smaller and depends on the amount and nature of non-conductive contaminants at the contact interface.
A second analogy can be made by comparing the pressure drop of water current streaming through a shower head to the voltage drop of electrical current through a cluster of a-spots in the contact zone [8]. The size of the holes in the shower head is then compared to the a-spot diameters, their size depends on the normalforce and hardness of the surface layer (usually the plating layer). The cluster diameter compares to the shower head diameter and depends on the normalforce, the contact radii and the base material. This diameter can be calculated using the Hertz theory. Fig. 2 shows graphs of the Hertz stress and spot diameters as a function of normalforce. Plating layers are generally thin compared to the Hertz stress distribution; their behaviour is therefore like a membrane on top of the elastically deforming substrate.



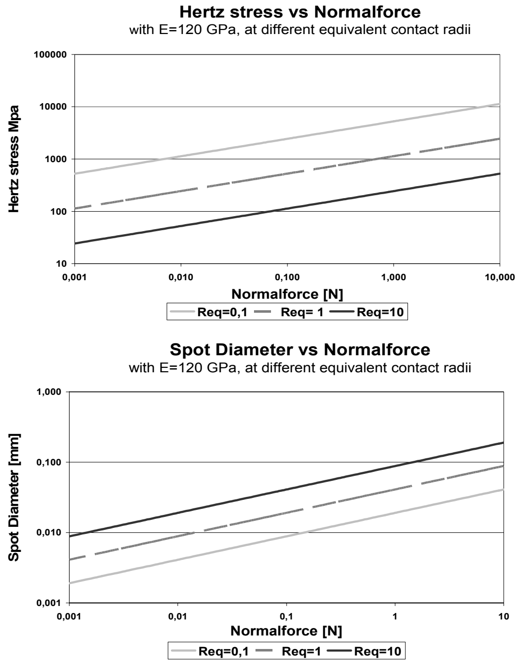


Fig. 2. Hertz stress and contact spot diameter versus normalforce for different values of the equivalent contact radius according to the Hertz theory (sphere to flat).

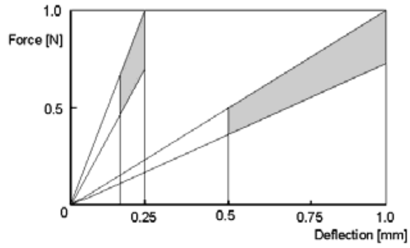


Fig. 3. Examples of two spring characteristics: the normalforce depends on the spring deflection and on the spring rate and their respective tolerances.

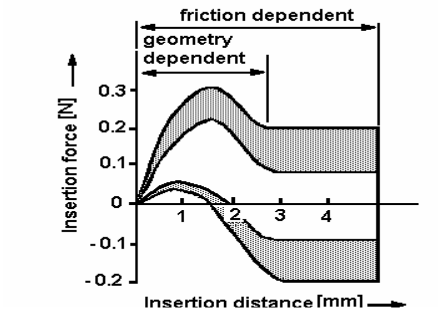


Fig. 4. The insertion force depends on the normal force, the contact geometry and on the co-efficient of friction

4. Contact Mechanics

Contact mechanics involves two factors, achieving and maintaining forces and controlling the effect of motion.
Achieving a normalforce is generally done by deflecting a spring. This introduces tolerances on the spring deflection as well as on the spring rate; hence inside and between production lots the normalforce will have a certain range wherein it varies. The graph of Fig. 3 gives two examples of spring characteristics where such a tolerance range is shown. The graph in Fig. 4 shows a graph for the insertion and withdrawal forces, this range is even wider because not only the normalforce has a range, also the geometrical shape of pin tip and receptacle entrance and their tolerances have an effect on the peak force needed to load the spring. Also the friction coefficient has a direct effect on the insertion and sliding forces. The graphs show that force control is difficult, yet critical because low forces make contacts sensitive to effects of motion, dust and corrosion; high forces generate high insertion/withdrawal forces and high wear.
There are different causes for motion between contact surfaces. In the first place mating cycles will cause wear and can move corrosion or dust particles from the wear track into the contact area. Suitable test sequences including mating cycles, ageing and corrosion tests will predict whether a combination of materials, contact geometries and normalforce will survive a required number of mating cycles. A mating process should always incorporate some sliding action, the so-called "wiping motion", even in compression spring situations. This serves to deform and clean the contact surface and to push contaminants and dust aside. A wiping motion of 100 µm is generally sufficient [9]. It follows that there is always some wear involved and that only a limited number of insertion cycles can be withstood. The achievable number of mating cycles depends on surface materials, contact geometries, normalforce, insertion track length and friction/lubrication. Ideally the mating contact surfaces should not move other than during insertion/withdrawal cycles. The whole assembly that includes the connector must be considered from the point of view of whether potential causes of motion exist. Possible causes are differences in thermal expansion, shock and vibration, play in the construction and effects from external forces by insufficient strain relieve.

5. Contact Materials

The design requirements with noble metal surface material (gold, palladium or silver) are fundamentally different from those for non-noble metals (tin, nickel or copper alloys).

Important aspects with noble metals are a clean and smooth surface, a nickel under-coat, a well designed geometry and also a pore-free surface layer if corrosion is of concern. A normal force of 0.3 to 0.5 Newton is sufficient to make good contact on a clean surface; however a minimum of 1 N and redundancy of two parallel contacts are recommendable for a good reliability. At the longer term the major concern with noble metal contacts is to avoid pore corrosion and migration of corrosion products to the contact area. Further to keep the surface free from other contaminating substances such as dust.

Non-noble contacts have an oxide film on the surface and need much more force, 5-10 N, to disrupt the oxide film and make good contact. The notable exception is tin which is soft so that at relative low force the very thin oxide layer is broken and a large contact area formed. Tin may however transform into intermetallic alloys at higher temperatures and then higher forces are needed, like for the other harder non-noble metals, 5-10 N.

Advantages of non-noble metals are that pore corrosion is of less concern and that thanks to the higher force the surface roughness and contamination issues are less critical. A higher roughness can even be advantageous with tin plating because the valleys can act as sources of fresh tin during the wear process. The higher force also makes relative motion less likely to occur, however, when relative motion does occur then fretting corrosion will take place and fretting corrosion is the major failure mechanism for non-noble contacts [10].

6. Conclusions

1. *Many parameters influence the reliability of electrical connections.*
2. *Clean surfaces do not exist in the real world!*
3. *It is crucial to make contact with sufficient force and with a wiping motion; further to avoid undesirable relative motion at the contact interface afterwards.*
4. *Non-noble metals have an oxide-layer at the surface and require higher forces than noble metals; also they are more sensitive to cyclic motion at the interface.*
5. *Noble metal contacts require less normalforce and are only sensitive to cyclic motion after wear-through of the noble surface coating.*
6. *To avoid the high cost of failure of equipment it is important that contact system designers have a good understanding of electrical contact theory and of material properties. This will also help to perform well designed tests and investigations.*

References

[1] *Vincent C. Pascucci.:* "A Brief Overview of Reliability in General and for Electrical Connectors in particular" Tyco Electronics catalog nr 296578, 2004

[2] *R. Holm:* "Electric Contacts", Springer Verlag, 2000

[3] *J.G.Zhang, J.G.Gao, C.F.Feng*: "Adhesion and Attaching of Particles at the Failed Connector Contacts". Proc. ICEC-Conf. 2006

[4] *Bob Mroczkowski*: "Concerning Estimating Connector Reliability: Laboratory Simulations and Reliability Modeling" Proc. Holm Conf, 1998

[5] *Williamson, J.B.P.:* "The Micro-World of the Contact Spot". Proc. Holm Conf, 1981

[6] *Pendleton W.E., Tackett A., Korzeniowski L., Cvijanovich G.B., Williams R.T., Jones W.C.:* "STM Study of Topographical Changes on Gold Contact Surfaces Caused by Loading", Proc. Holm Conf., 1998

[7] *Dijk, Piet van:* "Contacts Spots", Proc. ICEC Conf. 2000

[8] *Dijk, Piet van:* "Critical Aspects of Electrical Connector Contacts", Proc. ICEC Conf. 2002

[9] *Brockman I., Sieber C., Mroczkowski R.:* "A Limited Study of the Effects Of Contact Normal Force, Contact Geometry, and Wipe Distance on the Contact Resistance of Gold-Plated Contacts", IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol 11, No.4, Dec. 1988

[10] *P .van Dijk and F .van Meijl:* "A Design Solution for Fretting Corrosion", 42nd IEEE HOLM Conf. 1996

The Author

Piet van Dijk received his M.Sc. degree in Mechanical Engineering from the Eindhoven Technical University in 1971. During 1973-1999, he worked in the AMP European Development Centre (EDC) in 's-Hertogenbosch, the Netherlands. In 1999 he founded PVDIJK BV, a consultancy company specialized in the field of electrical contacts and connectors. He became a member of IEEE and VDE in 2000. PVDIJK BV is based in the Netherlands, serving the market with advice, seminars, measurements and simulations for connector design.