Critical Aspects of Electrical Connector Contacts

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Abstract

The major challenge for the design of electrical connectors is to ensure a predictable, reproducible and satisfactory field performance. There are many aspects that need to be considered in the design process as well as in the research on electrical connectors to achieve reliable connector designs. Many investigations show seemingly contradictory results and demonstrate thereby that the results of experiments with a specific set of variables like force, contact shape and materials, cannot be transferred directly to other combinations of variables. There exist no well defined limits for parameters like normal-force, Hertz stress, maximum temperature, plating thickness, roughness and number of mating cycles. Because of all this the validity of the results of research experiments is limited and the experimentation and the interpretation of the results is very complex. A basic understanding of the underlying physical phenomena is therefore a must.
In this paper some analogies of the contact area will be presented in an effort to promote the understanding of the behaviour and the performance of electrical connectors. Subsequently the most important aspects of connector design and research are explained and discussed.

1. Introduction

Connector sales in the year 2000 amounted to about 30 billion Euro, about 15 billion of it in the computer, datacom and telecom markets and about 5 billion in the automotive market (source: Bishop & Ass.). The connector market is a very competitive market with many new challenges and a high price pressure. Every opportunity is used to save cost: smaller centerdistances, smaller parts, less material, cheaper material, thinner platings, lower normalforces[1], use of single sided contacts. However, it becomes a ridiculous situation when an expensive piece of equipment like a computer, a car, a telephone or a copying machine fails just because the penny saved on a connector was one too much. Of course, it is not just a matter of money alone. Far more important is having a sound basic understanding of what is needed for good contacts and a proper application. This basic knowledge is important for connector users and suppliers, but also for system designers who often consider connectors to be just a commodity item to be added in the latest stage of system design. Often it appears that cheaper **and** more reliable solutions would have been possible if the connection had been considered in an earlier stage of system design. Basic knowledge of contact physics is scarce, it resided in the past with big companies, to mention a few: Philips, Siemens, Ericsson, Bell Telephone and IBM. Many of these companies did not maintain their knowledge base and expected from their connector suppliers to have this basic knowledge. These suppliers in turn have cut back on their research resources for cost reasons. Presently there is a trend that big companies start gathering knowledge again. Not particularly because they like to do so, but to secure or sometimes restore the reliability of their products.
The intention of this paper is to collect and extend a part of the existing understanding by presenting analogies between a contact surface and a geological landscape and between a contact spot and a shower head. This will be followed by some paragraphs discussing important aspects involved in the design of connectors.

2. Analogies

In the middle of previous century Bowden and Tabor in 'The Friction and Lubrication of Solids' [1][2] present the basics of understanding friction. HOLM in his famous book 'Electric Contacts' [3] discusses electrical contacts more in particular. Contact surfaces are depicted as a collection of individual spots (so-called contact asperities or a-spots) where the current is transmitted from one surface to the other. Williamson in his paper 'The Microworld of the Contact Spot' [4] makes it more imaginable by comparing it to placing Vermont upside down on New Hampshire.

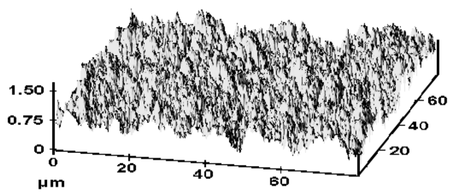


Figure 1 Surface roughness measured over a 80x80 μm area by Atomic Force Microscopy (Source: Wake Forest University[5][6])

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

Figure 1 shows a picture from an area of 80x80 µm of a metal surface made by atomic force microscopy, taken from a paper by Pendleton et. al [5][6]. Peaks are about 1 µm high. The vertical scale is strongly magnified compared to the horizontal scale, as also usual in roughness measurements.

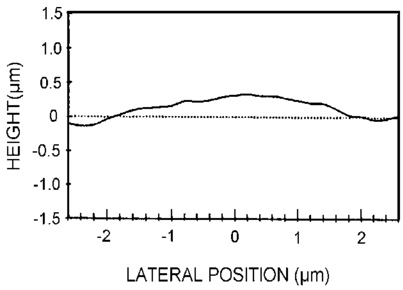


Figure 2 One representative peak from figure 1 with equal horizontal and vertical scales (Source: Wake Forest University)

In Figure 2 a representative example of one peak from the picture of Figure 1 is shown at equal horizontal and vertical scales. Only a length of about 5 µm can then be shown.

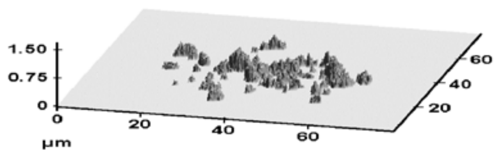


Figure 3 The missing peaks from the surface of Figure 1 after impression with a ruby ball with 0.8 mm radius and 1 N force (Source: Wake Forest University)

The picture of Figure 3 is made by taking the picture of figure 1 and subtraction from it a picture from the same surface after plastic deformation by an indentation with a 0.8 mm diameter ruby ball at 1 N normalforce. The base planes of the hills can be thought to form a cluster of a-spots in a contact area of about 40 µm diameter.

An analogy can be made between such a contact surface and a geological landscape by imagining a contact surface at hundred million times magnification. Then a surface area of 1x1 mm transforms to 100x100 km. A 1 µm thick plating layer on such a surface with a height difference of 1 µm transforms to a 100 meters thick layer of golf balls on top of 100 meters high hills.

A contact area of about 40x40 µm, like in Figure 3, is magnified 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 mostly much smaller real area of mechanical contact, depending primarily on the hardness of the surface layer. The electrically conductive area is even smaller and depends on the amount and nature of contaminants like oxides and organic matter at the contact interface. It is possible to compare the by microscope observed diameters of the cluster of a-spots from several investigations to the contact surface area that a calculation based on the Hertz theory predicts for elastic deformation and a smooth surface.

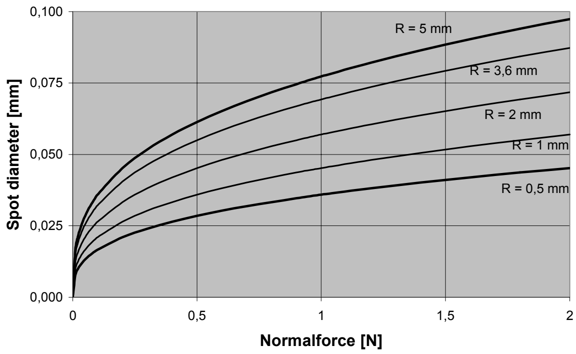


Figure 4 Contact spot diameter according to Hertz theory versus normalforce for different values of the contact radius (sphere to flat).

Figure 4 shows the spot diameter calculated with the Hertz theory , it predicts the diameter of the cluster of a-spots of 40 µm in Figure 3 quite well at 1 N and 0.8 mm.

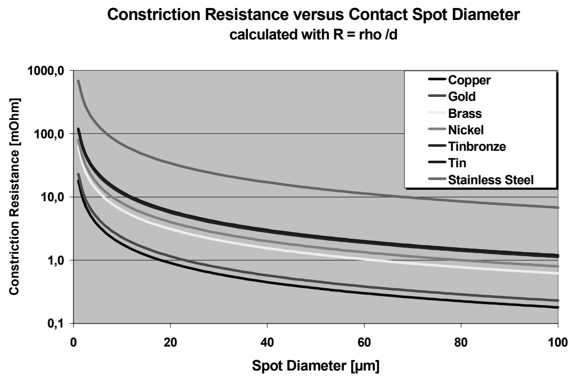


Figure 5 The theoretical relation between constriction resistance and spot diameter for a single circular contact area with a clean and smooth metal surface for various metals (The lines from tin and from tinbronze coincide)].

Holm[3] has derived and demonstrated that the constriction resistance of one solid circular spot depends on the specific resistance of the contact material divided by the diameter of the spot.

Figure 5 shows this relationship between the constriction resistance and the spot diameter for various materials. It makes clear that the metallic conductive area is indeed very small or even non-existent at high contact resistances. A contact resistance of for instance 1 Ω must be mostly film resistance, the curves show that there can not be a metal to metal contact area even as small as 1µm in diameter, because then the resistance would already be lower than 1 Ω.

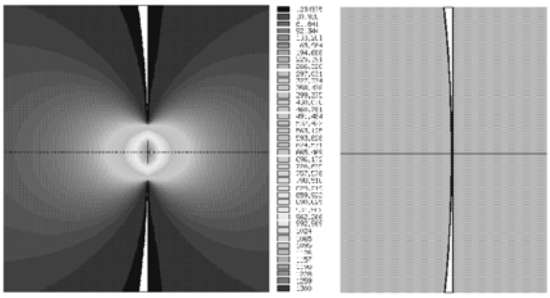


Figure 6 The picture at the right shows a solid model of a contact surface. The black line at the surface is indicative for the thickness of a plating layer. The picture at the left shows the Hertzian elastic stress distribution around the same contact spot as calculated with the finite element method.

Figure 6 shows how thin the plating layer generally is compared to the Hertzian stress distribution, it behaves like a membrane on top of the elastically deforming substrate.. A second analogy can here be made, now between the pressure drop of water current streaming through a shower head (or a filter in a conduit-pipe) and the voltage drop of electrical current through a cluster of a-spots. In this analogy the outer diameter of the head can be compared to the diameter of the cluster of a-spots and can be calculated by applying the Hertz theory to the elastically deforming substrate [7]. The size of the diameter of the cluster of a-spots is determined by the contact radii, the normalforce, the elastic properties of the base metal (modulus of elasticity and Poisson ratio) and the surface roughness (see also [8]). The holes on the shower head compare to the individual a-spots. The number and sizes of the individual a-spots depend strongly on the hardness of the surface material (mostly the plating layer), and also on the morphology of the surface, on the normalforce and on the contactradii.

In addition to these two analogies a lateral motion needs to be added to complete the picture of the analogies. Suppose a slow sliding speed of 1mm/s like in insertion/withdrawal tests. Magnifying this speed with the same magnification factor of 10^{8}, you have to imagine standing in a valley and looking up to a moving counterpart that passes at a height of about 70 meters above you with a speed of 360,000 km/hr. It will cause the ground underneath you to be depressed by 50 meters while the 4 km spot passes by in about 0.04 s. It is easy to imagine that lateral motion plays an important role in the formation of a much larger contact surface area than the normalforce alone would be able to generate. Of course this comparison is not entirely realistic, but it does confront us with our limited ability to imagine what happens on such small scales.

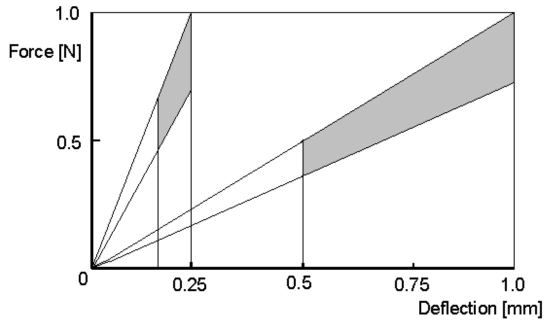
The so-called "wiping motion" has a strong surface cleaning effect, which is desirable, it is even a necessary condition for good metal to metal contact (Brockman et.al.[9]), however it causes also deformation and wear. An effective wiping motion makes metals touch each other so well that the flow of electrons is virtually uninterrupted, however it is a challenge to find a compromise between a good wiping action and low wear at multiple insertions.

In many investigations of electrical connectors contact resistances are measured without applying such a wiping motion. This is fine for the purpose of detection of surface films but it does not predict how contact materials will behave in real contacts after applying a wiping motion. In good simulation tests a wiping motion with a representative geometry must be included in the test program. See also lit.[10]

In summary it can be said that the in this chapter described analogies together with the considerations of motion and friction comprise the basis for understanding of the behaviour of electrical connector contacts.

3. Connector Design Aspects

3.1 Variation of insertion and normalforce



Figuur 7 Examples of two spring characteristics: the normalforce depends on the spring deflection and on the spring rate and their respective tolerances.

Figure 7 shows two different spring characteristics, one with a relative small deflection, the other one with a much larger deflection. High spring rates, stiff springs, are mostly used in two piece connectors where the dimensions of pin and receptacle can be well controlled. More resilient springs are used when electrical contact is required between parts that are assembled together, like a battery in a mobile phone. In both cases the difference between minimum and maximum force is surprisingly large. Often it is not well understood that insertion forces and normalforces can vary widely from batch to batch, *even if all individual dimensions are within narrow tolerances*. The reason is that the normalforce is the result of the multiplication of two main factors:

- The spring deflection, which varies with tolerances on pin thickness and receptacle gap size
- The spring rate, which varies with tolerances on the modulus of elasticity, the spring length, the spring width, the spring thickness and the elasticity of the fixation.

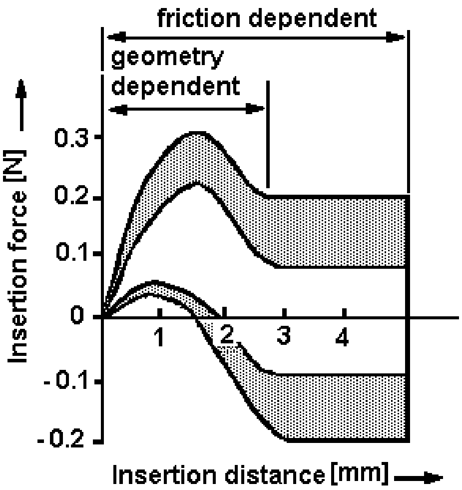


Figure 9 The insertion force depends on the normal force, the contact geometry and on the co-efficient of friction

The maximum insertion force depends on the two factors in the normalforce and two more factors, see also figure.9:

- The geometry of pin tip and receptacle entry
- The coefficient of friction

All four factors, together consisting of in the order of ten individual dimensions, need to be in tight control in order to keep the insertion force within its design limits.

3.2 Normalforce and geometry

Often the question is raised whether it is the force or the stress in the contact area which is more important as a contact design parameter, and my answer is that both are important in their own way.
A practical difference between the two parameters force and stress is that the force can directly be measured while stress can only be derived indirectly from normalforce and geometry or from the yield stress of the surface material.
The normalforce is considered the most important parameter to determine the performance of a contact. It is common practice to specify a minimum normal force and a minimum plating thickness to ensure good reliability. This is indeed sufficient for incoming goods inspection provided that the geometry and other conditions (also lubrication) are specified and fixed after passing a release test that simulates the future use of the equipment.
Papers by Kantner and Hobgood [11], Fluss [12] and Mroczkowski[13] show clearly the difference in wiping effect and wear behaviour with different geometries at the same normalforce.

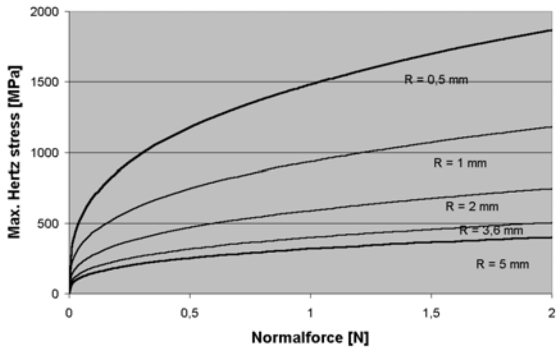


Figure 8 The Hertz stress as function of the normalforce at various values for the contact radius

The suggestion is made that about 1000 Mpa is a good value for the maximum Hertz stress. The maximum Hertz stress is of course a theoretical value for a maximum stress based on the assumption of elasticity and surface smoothness. *It expresses the degree of concentration of force*. It is of importance for the effectiveness of the wiping motion. The real stresses at the interface can be approximated by measuring the plastically deformed area and divide the normalforce through this area. The result is then approximately equal to the yield stress of the surface layer (including work hardening).

3.3 Motion of 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 location 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 Dijk and van Meijl [14] [15], by Kassman Rudolphi and Jacobson [16] and by van Dijk et.al. at this conference [17] 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. Also Abbott points in one of his excellent publications to the importance of relative motion as a cause of failure[10].
It follows that a more detailed analysis of causes of motion is important.

Four causes of motion can be distinguished:

➢ *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. An important consideration is the trade-off between a high force combined with a sharp geometry to penetrate through non-conductive surface films and a low force combined with round geometry to achieve low 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 differences in 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.

Wear and the effect of underplate and substrate and lubrication are investigated and discussed in papers by Antler [18] and by Antler and Drozdowicz [19].

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

In hand-held devices, for example mobile phones, battery connections are often mounted with some 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 dependent on the user and can easily add up to ten thousands of cycles over a 5-year life cycle, much more than would ever be specified as a number of insertion cycles.

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

Temperature changes combined with differences in co-efficient of thermal expansion can very well lead to relative motion at the contact spot. Long card edge connectors and IC-sockets are examples where such phenomena occur. The number of cycles depends on the application, but a number of thousands for a life cycle of a product is likely.

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

It is known that large printed circuit boards mounted in a rack and connected with edge or two-piece connectors sometimes arrive with worn-through contacts from transportation by truck or train. Also the connections to vibrating car and truck engines require extreme careful design to avoid problems of relative motion and fretting corrosion. The number of fretting cycles will be exceedingly large when relative motion takes place: there are 36.000 cycles per hour with frequencies as low as 10 Hz!

3.4 Noble and non-noble contact materials

The design requirements for noble metals are fundamentally different from those for non-noble metals.

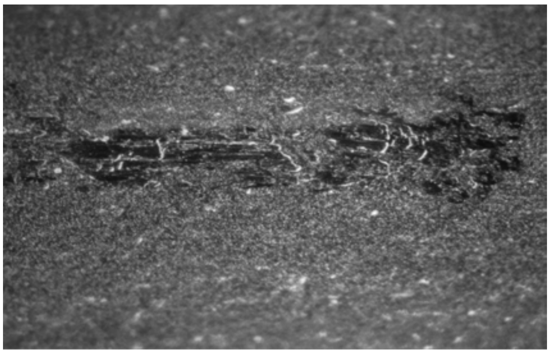


Figure 9 Wipe track after one pass on gold-plating with a contact radius 1.4 mm and normalforce 2 N. Only the central part of the wipe track is locally plastically deformed, the track width is about 45 μm.

Figure 10. Wipe track on soft tin-plating with a contact radius 1.4 mm and normalforce 2 N after one pass.. The whole wipe track is plastically deformed. The track width is about 80 μm.

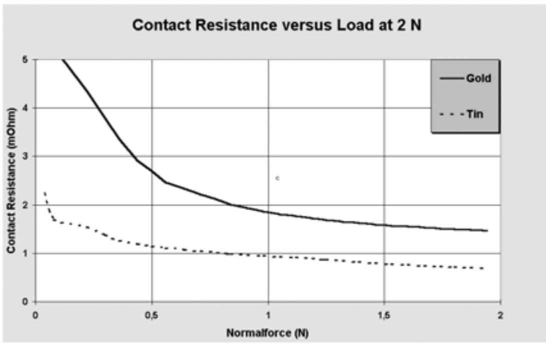


Figure 11. Contact Resistance versus Normalforce measurements during the loading phase of the gold and tinplated contacts from figures 9 and 10. Fresh tin is so soft that the contact resistance is lower and more stable than with gold, while the specific resistance of tin is much higher than that of gold.

Important aspects with noble metals are a clean and smooth surface, a well designed geometry and a pore-free layer if corrosion is a concern. A normal force of 0.3 to 0.5 Newton is sufficient to make good contact on such clean surface (see figures 9, 11 and 12), however for a good reliability the previously commonly required minimum of 1 N and redundancy of two parallel contacts is still a good recommendation, particularly when short interruptions are of concern.

At longer term the major concern with noble metal contacts is to avoid pore corrosion and keep the surface free from contamination.

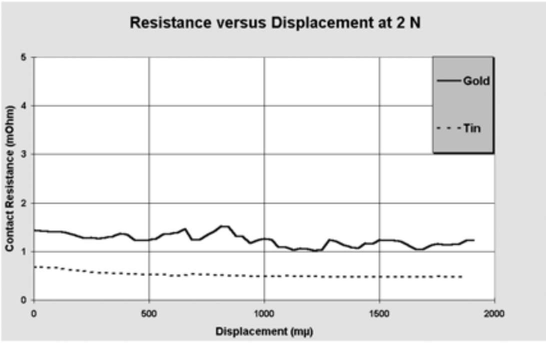


Figure 12. Contact Resistance versus Wipe Distance measurements during the wiping phase of the gold and tinplated contacts from figures 9 and 10. Fresh tin is so soft that the contact resistance is lower and more stable than with gold, while the specific resistance of tin is much higher than that of gold.

Non-noble contacts behave fundamentally different. They 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 so soft that at relative low force the very thin and hard oxidelayer is broken and a large contact area created (see figure 10, 11 and 12). Tin may however transform into intermetallic at higher temperatures and then higher forces are needed, like for most other harder non-noble metals, 5-10 N.
Advantages of non-noble metals are that pore corrosion is of no concern and that thanks to the higher force the surface roughness and contamination are less important.
With tin plating a higher roughness can even be advantageous, 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. Fretting corrosion is the major failure mechanism for non-noble contacts, see also lit. [17].

3.5 Current, Voltage and Frequency

The electrical conditions determine how critical the different parameters are in a certain application. For high currents the contact and constriction resistances need to be low to avoid overheating of the contact point. For low currents there is no special contact problem. With voltages it is the other way around: with high voltages the connection is not critical because fritting will improve the contact if the dry circuit resistance is too high, while with low voltages high resistances may cause problems. With the increasing use of high frequencies several new problems have arisen. Short interruptions may switch equipment off or distort a data flow. Also contacts for shielding and grounding, for example in coax connections, become very critical and do no longer allow resistive and unstable connections from grounds and shields as it leads to common path distortion problems.

3.6 Lubrication and Corrosion

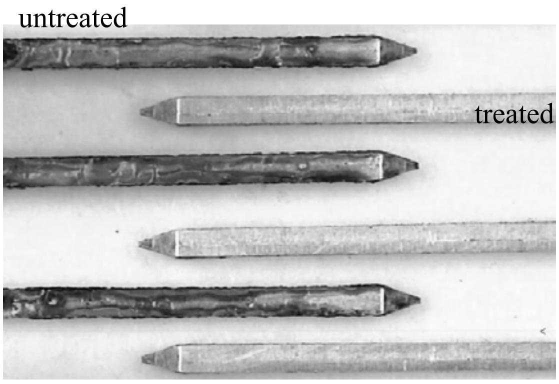


Figure 13. Untreated posts with a porous gold plating corrode heavily in a Flowing Mix Gas test, while posts from the same batch survive surprisingly well in the same test environment when treated with a conservating lubricant.

Lubrication is a complex subject. Many papers treat a large number of aspects, see lit. [19-24]. Lubrication is in most applications advantageous to electrical contacts because of lower insertion forces, less wear and with special additives also less corrosion, see figure 13. Lubrication has disadvantages as well, a lubricated surface may retain more dust, the wiping motion may get less effective, the lubricant may enable sliding micro-motion where this would not take place without lubrication, lubricants can polymerise and form insulators, it can form a varnish, it can creep to places where it is not wanted. Proper and controlled application is a difficult theme. When applied before assembly it may be partly removed during the assembly process, but after assembly the contacts are mostly less accessible. Also housings and packaging materials may become contaminated with lubricant. The thickness is known to be important for the electrical function, however it is hard to measure and hard to control, initially and also once a few mating cycles have taken place.
Lubricants must still be considered to be a part of the product surface finish, to be specified on the product drawing and subjected to the procedures of testing and quality control, like any other finish.

4. Conclusion

Many parameters influence the reliability of electrical connections. It is vital to have a thorough understanding of electrical contact theory and to perform well designed tests and investigations in order to avoid the high cost of failure of equipment.

5. Literature

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