Contact Spots

Piet van Dijk

Abstract ---This paper intends to provide insight in the size of the spots of mechanical contact and the distribution of stresses near the contact point in electrical contacts. It will be shown that the elastic behavior of the bulk material in combination with the plastic behavior of the plating layer(s) govern the size and shape of the contact area(s).
The normalforce, the curvature of the mating contacts and the modulus of elasticity of the bulk of the material determine the Hertzian stress distribution and thereby the size of the diameter of the cluster of contact spots. The Hertz theory accurately predicts the size and shape of the cluster of contact spots and the stress distribution in the bulk material. However the underlying assumptions of a smooth surface and total elastic behavior are not fulfilled near the surface of the contact. This implies that we have to incorporate the effects of roughness and plasticity into the contact model separately.
We can use the Hertz theory as a basis and superimpose the surface effects. How this can be done is demonstrated in three examples with various shapes and plating materials. The combined model can serve to understand and optimize the effects that normalforce and contact shapes have on wipe effectivity and wear properties of electrical contacts.

Key words: a-spots, Hertz stress, contact radius, wipe, wear, normalforce

I. Introduction

Early studies, particularly from Greenwood and Williamson [1,2,3] describe a contact area as consisting of a multiplicity of small spots, called a-spots, and help greatly in understanding the phenomena at contact interfaces.
The diameter of the cluster of a-spots mostly determines the constriction resistance and also the stress level near the interface (at a given force). It is of interest to compare the observed diameters of the cluster of spots from previous investigations to what a calculation based on the Hertz theory would predict. The cluster diameter is determined by the contact radii, the normalforce[1], material properties (modulus of elasticity and Poisson ratio) and surface roughness as already noted in [4] and [5]. An example of such a cluster of spots is also shown in a recent paper at the 44th IEEE HOLM conference (1998), by Pendleton et. al., titled "STM Study of Topographical Changes on Gold Contact Surfaces Caused by Loading" [6].
The most important parameters are the contact radii and the normalforce; together they largely determine the so-called Hertzian stress distribution. The Dubbels Taschenbuch [7] gives simplified formulas for spherical and cylindrical contacts. Deeg, in a paper in the AMP Journal of Technology [8], has adapted the calculations of contact spot diameter and Hertz stress for personal computers, so that it has become easy to do, even for elliptical cases and crossed rod configurations.
The cases from the Loughborough [4], Nuremberg [5] and Wake Forest University [6] publications were selected to verify the validity of these calculations for electrical contacts. The observed contact zones are compared with predictions from Hertz stress calculations.
I will show how the effect of the surface layer can be combined with these elastic stress considerations and discuss some consequences for the contact performance.

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

II. The Hertz theory

Given two smooth spheres of equal diameter pressed together, with limited force so that stresses remain below the yield stress (see Fig. 1), one can easily see that the interface between the spheres is a circular area. Also that this interface is flat in the case of equal radii. The diameter of this circle depends on the normalforce. The elastic deformation is achieved by elastic compression of the bulk material underneath. The relation between stresses and strains is linear, with the modulus of elasticity defined as the ratio of stress and strain (Hooke's Law)
Dubbels Taschenbusch [7] gives the Hertz formulas for the maximum stress and the radius of the circle of contact area:

$$\sigma_{max} = (1/\pi)*(1,5*P*E^2/(r^2*(1-\nu^2)^2))^{1/3} \qquad (1)$$

$$a = (1,5*(1-\nu^2)*P*r/E)^{1/3} \qquad (2)$$

Where:
σ_{max} = maximum stress or Hertz stress [MPa]
P = normalforce [N]
E = modulus of Elasticity [MPa]
r = $r_{equivalent}$ with $1/r_{eq} = 1/r_1 + 1/r_2$.
r_1 and r_2 are the radii of the two spheres [mm]
ν = Poisson's ratio ≅ 0.3
a = radius of circle of contact [mm]

In the case that parallel cylinders are pressed together a line contact is formed. The cross section of the stress distribution is of parabolic shape. The difference with a point contact is that the interface is of rectangular shape and the stresses are an order of magnitude lower due to the longer length of the stress distribution. Stamped and formed line contacts generally do not have a uniform contact pressure over the full length; they are mostly less well defined than point contacts.

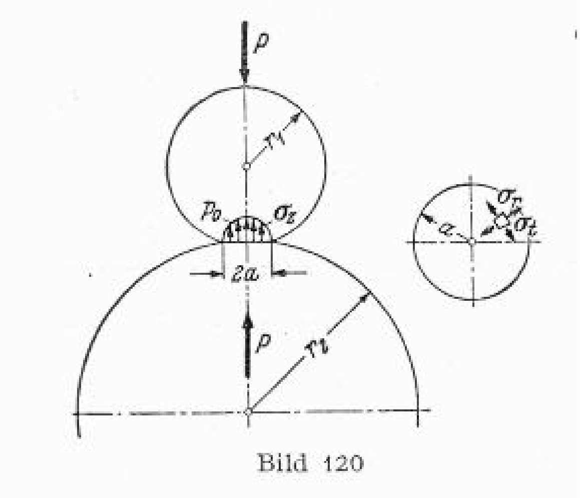

Fig. 1. Stress distribution between two spheres [7]

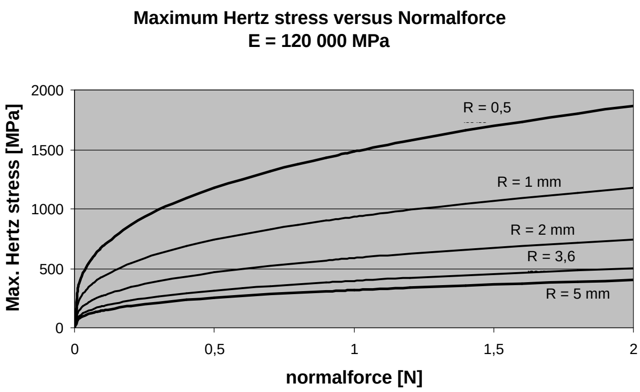

Fig. 2. Maximum Hertz stress as a function of normalforce, according to formula (1)

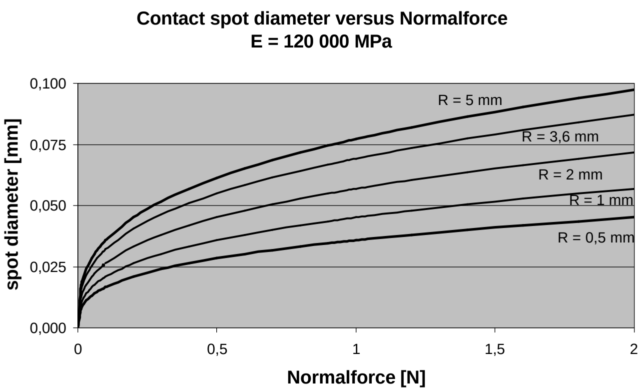

Fig. 3. Contact spot diameter according to the formula (2)

The formulas (1) and (2) do not apply to elliptical situations. In such more complex cases software can be used based on a publication by E.Deeg [8], an article that according to its author could have been subtitled: “What if Heinrich Hertz would have had a personal computer?”

For symmetrical cases the results from this program are of course identical to the results from the formulas (1) and (2).

III EXAMPLES

Example 1.

The first example that I want to discuss is taken from my previous publication in Loughborough [4].

I showed wear tracks made with a sphere-to-flat configuration, normalforces of 1, 2 and 5 N, for respectively gold plated, tin plated and unplated contacts. The contact radius was 3.2 mm.

Results from Hertz calculations for this configuration are listed in table 1.

Force [N]	Cluster diameter [μm]	Max. stress [MPa]
1	66	436
2	83	549
5	113	745

Table 1. Results from Hertz stress calculation with 3.2 mm radius and modulus of elasticity 120 000 MPa

The wipe track with 1 N normalforce on the gold plated contact is slightly wider than the theory suggests, 80 μm instead of 66 μm, see Fig. 4.

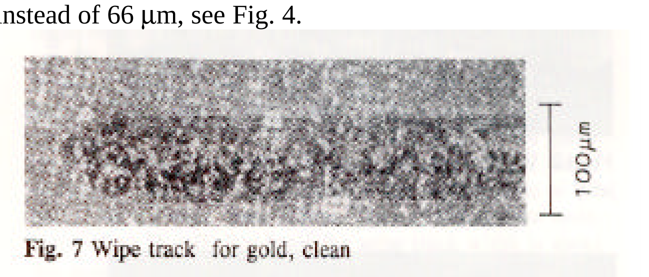

Fig. 4. Wipe track with gold plated contacts and a normalforce of 1 N.

This increased width can be explained very well by the effects of:

- roughness
- shear stress due to friction under motion.

I measured the roughness in this particular case and compared this roughness height to the radius and contact spot dimensions, as shown in Fig. 5.

With tinplated contacts and 2 N normalforce, the wipe track widens during wiping because of the strong plastic deformation of the very soft tin layer combined with a high coefficient of friction (Fig. 6). The calculated spot width of 83 μm (table 1) is in good agreement with the track width at the point wear initial contact is made, considering the effects of softness of tin and roughness.

During the wiping motion the 3.5 μm thick tin layer deforms and the crown of the radius flattens. The hardness of the tin is so low that the plating thickness now plays an important role and the contact spot size is no longer determined by the Hertz stress alone.

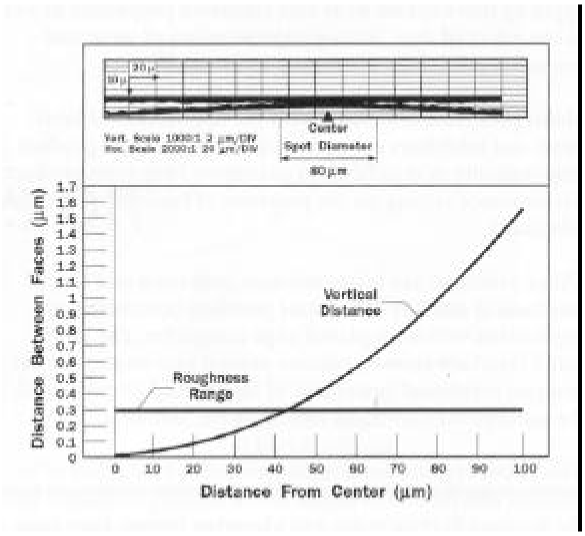

Fig. 5. Graph showing the measured roughness (top part) and the roughness range compared to the theoretical distance between undeformed surfaces (lower part)

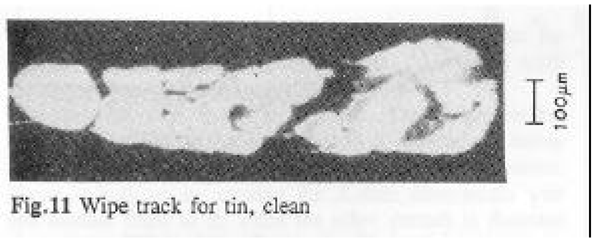

Fig. 6. Wipe track with tin plated contacts and a normalforce of 2N.

With unplated tinbronze and 5 N normalforce the Hertz calculation predicts a track width of 113 µm. Fig. 7 shows a width of about 130µm. The result of this comparison is quite reasonable considering that there is an effect of plastic deformation because of shear stresses during wiping. The effect of roughness is getting less important at higher forces.

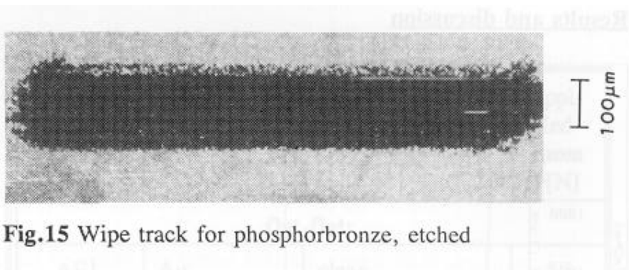

Fig. 7. Wipe track with unplated contacts from CuSn6 and a normalforce of 5 N.

Example 2

The second example is a gold over nickel plated tinbronze contact with a crossed rod geometry, the receptacle has a radius of 0.75 mm, the pin has a radius of 0.35 mm. Formulas (1) and (2) cannot be directly applied because of the elliptical shape of the contact area. Applying an average contact radius of 0.55 mm and a normalforce of 0.7 N in formula (2) predicts a contact cluster diameter of 33 µm. The contact ellipse can be calculated exactly using the program as proposed by Deeg. This results in a value for the length of 40 µm and for the width of 24 µm. I showed this second example in my presentation in Nuremberg, however it was not included in the proceedings due to time pressure. Fig. 8 shows the arrangement of the two cylindrical surfaces, mated in a crossed rod configuration. The 0.35 mm radius of the pin is perpendicular to the plane of the cross-section and cannot be seen. Fig. 9 shows a SEM picture from a cross-section through the contact interface of Fig. 8. From this picture the prediction of 40 µm length appears very accurate.

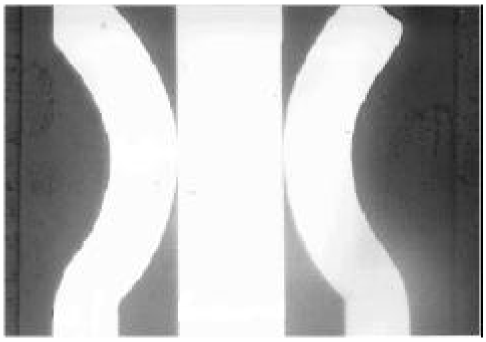

Fig. 8. Cross-section of pin and receptacle. The pin thickness is 0.4 mm, the receptacle material is 0.25 mm thick. The receptacle has a contact radius of 0.75 mm.

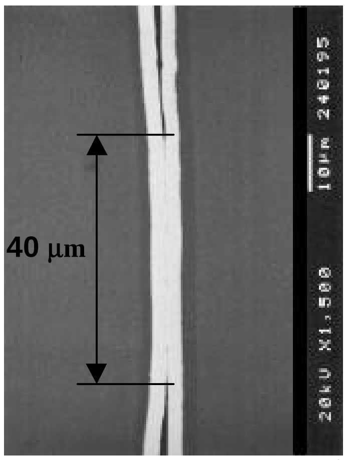

Fig. 9. SEM picture showing the cross-section of Fig. 8 at larger magnification with the gold (white) and the nickel layer (dark grey) near the contact point

This pin-receptacle combination has also been modeled and analyzed. The left side of the picture in Fig. 10 shows the distribution of von Mises stress in the material of the pin, and the picture at the right side shows the solid (computer) model. The thickness of the plating layer is the dark line at the contour, and is at the same scale as the picture at the left.

From this comparison it is clear that the cluster size is large in diameter (40 µm) and depth (100 µm) when compared to the thickness of a plating layer (1-2 µm). The plating layers behave like a membrane and it is obvious that the values of the modulus of elasticity and Poissons' ratio from the bulk material should be used in the calculations of elastic deformation. Also one has to keep in mind that the Hertz stresses in these calculations are the stresses perpendicular to the contact surface and can be much higher than the specified values for yield stresses, because yield stresses refer to von Mises stresses[2].

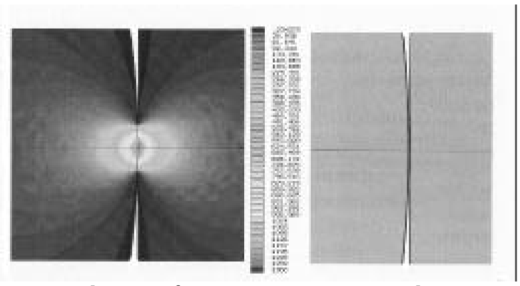

Fig. 10. Distribution of von Mises stress near the contact area (left) and a computer model showing a 1 µm thick plating layer (right, dark contourline)

Example 3

Another example is taken from a publication by Pendleton et.al.[6]. Scanning tunneling microscopy has been used to show the deformation of a flat contact surface after mating with a 1.6 mm ruby sphere at normalforces of 0.1, 0.25, 0.5 and 1 N. That resulted in a number of excellent pictures that stimulate visualisation of the contact surface. It gives data to verify the validity of the Hertz calculations and reason to comment on the plastic behavior of the surface layers. The first picture (Fig. 11) shows the STM picture of the deformed layer. Due to the enormous vertical magnification the surface looks mountainous like the Alps, however Fig. 12 shows the realistic proportion with equal scales horizontally and vertically. It is mentioned in ref. [6] that typical slopes range from 5-20 degrees. Fig. 14 shows the plastically deformed surface areas and the authors of the article note that the force divided by the area amounts to 2780 MPa, much higher than the 150-400 MPa that they expected from literature. They conclude that 80-90% of the load is carried by elastically deformed asperities or those that are plastically deformed to a lower degree than the measurement threshold in their experiments.

I regard such a large contribution of elastic stresses as highly unlikely and believe that the local stress level on cobalt hardened gold is underestimated. The roughness profile in Fig. 12 shows a representation of a typical high area, with a contact radius of about 5 µm. It follows according to Hertz that if this hill is touched by a hill at the other side it yields plastically at very small deformation. Forming a contact spot of only 0.3 µm diameter elastically requires a stress level of about 2700 MPa! The elastic flattening is in this case only 0.01 µm!

[2] Von Mises stresses are tensors calculated from the differences between the stresses in three independent directions and represent the tendency for plastic yielding.

I conclude that the yield stress, measured at this scale and in this way, is much higher than 150-400 Mpa. An article from Fluehmann [9] mentions 2130 MPa and 2660 MPa (217 kgf/mm^2 and 271 kgf/mm^2) under compressive stress. The stress level will exceed the commonly listed maximum yield stresses, because of work hardening, and because the yield stress under compression can be much higher than the yield stress in tension.

The observation in [6] that force increases in an almost linear fashion with surface area (Fig. 7a in [6]) is another indication that elastic stress does not play such a big role.

Let us take a look at the size of the spot. Hertz calculation predicts a contact spot diameter of 46µm and a maximum Hertz stress of 901 MPa. The contact spot diameter of 46 µm is almost exactly what we see in Figs. 11, 13 and 14.

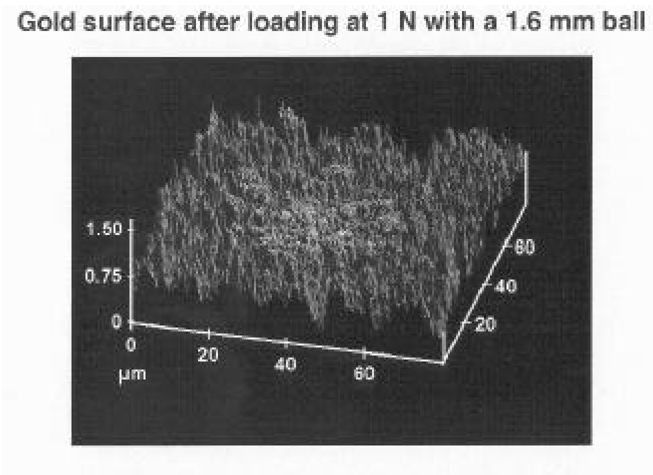

Fig. 11. Surface impression from a 1.6 mm ruby ball on a 1.25 µm gold layer over 1.25 nickel over a tinbronze (CuSn6) substrate. [6]

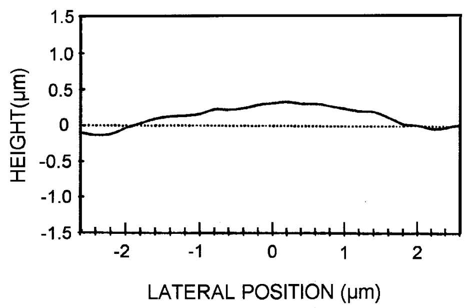

Fig. 12. A proportional representation of a typical peak from Fig. 11 [6]

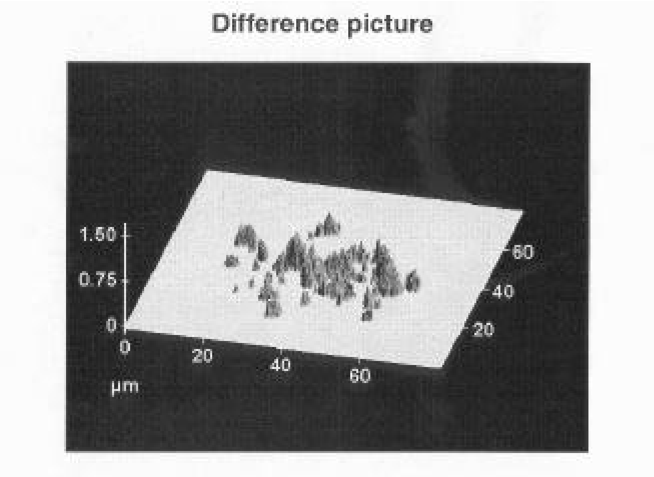

Fig. 13. The profile from Fig. 10 deducted from the undeformed profile, representing the changes due to the plastic deformation caused by the ruby ball [6]

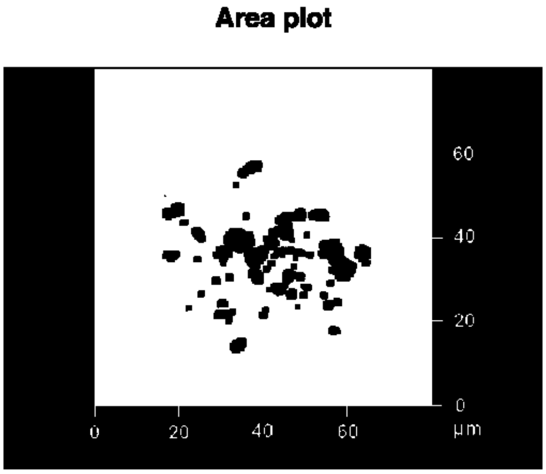

Fig. 14. Area plot, showing the projection onto the lateral plane of the difference picture of the change produced by indentation [6]

IV Discussion

In the real world we will generally not see smooth spheres and parallel surfaces, but various combinations of flat, spherical, elliptical and cylindrical surfaces. We can generalize these into point contacts and line contacts. At a given force there is an order of magnitude difference in Hertz stress between these cases. It is quite understandable that Kantner and Hobgood [10] find that field data at low forces (≤1 N) show that point-to-point contacts are more reliable than line contacts. They made a slight mistake when they used the modulus of elasticity of the plating layers in their Hertz stress calculations.

The reality in contact physics is too complex to use the Hertz stress simply as an indicator for contact performance as they propose. Mroczkowski [11] and Fluss [12] explain this very well in their respective articles.

Hertz stress considerations remain useful insofar that the combination of normalforce and Hertz stress says something about two important performance aspects: wipe effectivity and wear behaviour.

A sharper radius will improve the effectivity of the wiping motion as demonstrated by Brockman, Sieber and Mroczkowski [13]. However, a sharper radius is also likely to increase wear. For contact designers the challenge is to find the right combination of normalforce and contact geometry to have as well a good wiping action as sufficient wear resistance.

At low normalforce these considerations become more critical, especially when low normalforce combined with high compliance makes contacts move more easily. In the presence of contaminants geometries with larger radii tend to let contacts ride on top of contaminants rather than push the contamination aside, thereby causing intermittences.

V Conclusions

1. The Hertz stress calculation predicts the diameter of the contact spot cluster very well.
   Doubling the force generates a 26% increase of stress level and cluster diameter.
   Reducing the radius to half of its size increases the stress level by 59% and the cluster diameter by 26%
2. Increasing the surface roughness increases the cluster diameter. This effect is mostly of secondary importance.
3. It is the plastic deformation that determines the sum of the surface areas of individual spots.
   Doubling the force doubles this sum of areas in two ways, individual areas grow and the number of areas increases as well.
4. Increasing the Hertz stresses in a given configuration makes the wiping motion in electrical contacts more effective.
5. Increasing the Hertz stress in a given configuration will increase the sliding wear of electrical contacts.
6. Hertz stress should not be regarded as a design parameter, but rather as a design consideration.
7. The modulus of elasticity of the bulk material must be used in Hertz stress calculations; the properties of plating layers do not play a significant role. (Except for calculations on individual a-spots)
8. The stress at the interface is locally much higher than the generally specified macroscopic yield stress

Acknowledgements:

I thank Brian Williamson and Emil Deeg for reviewing the concept, Bill Pendleton and his co-authors for sharing their pictures and the colleagues of the Brite-Euram ELECON group for their review and valuable discussions of this theme.

VI References

[1] *Greenwood, J.A. and Williamson J.B.P.*: The Contact of Nominally Flat Surfaces, Proc. Roy. Soc. 295a, pp 300-319, 1966

[2] *Williamson, J.B.P.*: The Micro-World of the Contact Spot. Proc. Holm Conf, 1981, pp. 1-10

[3] *Williamson, J.B.P. and Greenwood J.A.*: The Constriction Resistance between Electroplated Surfaces, Proc. Int. Conf. on Electrical Contacts and Electromechanical Components, 1989, pp. 563-568

[4] *Dijk, Piet van*: Some Effects of Lubricants and Corrosion Inhibitors on Electrical Contacts, Proc. ICEC Conf., 1992, pp. 67-72

[5] *Dijk Piet van*: Contacts in Motion, ICEC Conf. 1998, pp. 123-127

[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, pp. 109-119

[7] *Sass F., Bouché Ch., Leitner A.*: Dubbels Taschenbuch für den Maschinenbau, Springer Verlag 1963 , teil 1, pp. 412

[8] *Deeg E.W.*: New Algorithms for Calculating Hertzian Stresses, Deformations, and Contact Zone Parameters, AMP Journal of Technology, Nr 2, 1992, pp. 14-24

[9] *Steinemann S., Flühmann W., and Saxer W.*: Verschleißverhalten und Struktur von galvanischen Edelmetallniederschlägen, Metalloberfläche, Heft 4, 1975

[10] *Kantner E. and Hobgood L.*: Hertz Stress as an Indicator for Connector Reliability, Connection Technology, March 1989, pp. 14-22

[11] *Mroczkowski R.*: Concerning "Hertz Stress" as a Connector Design Parameter: a Negative Vote, Proc. 24th Annual Connector and Interconnection Technology Seminar, Oct. 1991

[12] *Fluss H.S.*: Hertzian Stresses as A Predictor of Contact Reliability, Connection Technology, Dec. 1990, pp 12-21

[13] *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,