A Novel Method for Accurate Measurement of Elastic and Plastic Properties of Contact Spring Materials

Piet van Dijk, PVDIJK Consultancy BV, The Netherlands

Summary

For electrical contacts a certain normalforce* is needed to achieve reliable connections. Normalforces are mostly generated by contact springs, which are deflected a certain distance to produce the required normalforce. The prediction of the spring characteristics is a critical design issue.

This paper describes a novel method (for ease of speech the “PD” bend test) to measure the spring properties for connector materials in a bending test, using small test samples, 10x10 mm square and 0,1 to 0,40 mm thick. With this method the spring properties can be measured in two directions, the rolling direction and the transverse direction, and both the elastic and the plastic properties. The method forms a basis for very accurate predictions of contact spring characteristics, because it is more similar to the application than the tensile test. Also a multilayer, like a plated material, can be tested. This method should be regarded as an application related test; it is not intended as a replacement for the tensile test.

For electrical contacts it can enable the application of less costly or environmentally friendlier materials, or alternatively lead to the design of springs with smaller dimensions.

Measurement results are presented and discussed for 10 contact spring materials. It is concluded that, the proposed test delivers valuable data to product designers in the conceptual stage, though it should be further optimised.

Key words: *Contact Spring, Modulus of Elasticity, Elastic deformation, Plastic deformation. Anisotropy, Reverse bending, Bauschinger effect*

1. Introduction

Contact springs are commonly stamped and formed from rolled copper or steel alloys. The spring properties are determined by two factors; the geometry and the material. The geometrical component includes the shape and the fixation of the spring. The second component, the material component, includes the elastic and the plastic material behaviour.

In general two areas can be distinguished in force-deflection curves. The first linear area represents the elastic behaviour where the ratio of force (P) to deflection (d) represents the stiffness of the spring. In the second area of the curve, at higher force, the spring characteristic bends downwards due to plastic yielding and turns into a horizontal part where the spring yields at a more or less constant force. This yield level is of interest to the spring designer because an accurate prediction of this level and of the transition to this level enables him to optimize the spring in terms of stiffness and strength.

A spring with its length axis in the rolling direction will have different characteristic from a spring of identical design oriented in the transverse direction. Therefore anisotropy, the difference in elastic and plastic properties between the rolling direction and the transverse direction, is to be taken into account.

Finite element programs allow an exact geometrical description of contact springs including their fixation and the effect of deformation on the shape. Also anisotropy can be accounted for in these programs, provided that the material data are available in both directions. These programs use the stress-strain curve of materials to do simulations into the plastic range.

Forming and bending in the manufacturing process of contact springs can also have an effect on the spring properties. Residual stresses have either a positive or a negative effect on the onset of plasticity, depending on their direction. On top of that the so-called Bauschinger effect can lower the yield stress. The Bauschinger effect involves that deforming plastically in one direction generates dislocations to move at lower energy when deforming afterwards in the opposite direction [1]. Finite element programs do normally not account for these phenomena.

Also, finite element programs can only be used when a computer model of the spring is already generated. Reliable values of the modulus of elasticity and of the plastic yielding behaviour are already important in the process of generating a first spring concept.

An attractive method for connector spring designers to refine their predictions in the conceptual stage can be to perform bending tests on actual strip.

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

Bending tests have the advantages of having a stress distribution similar to that of contact springs and of being easier to carry out in transverse direction on small samples than tensile tests. Also a multilayer material, like for example a nickel plated material copper alloy, can be tested with this method.

2. Discussion of existing methods

2.1. Tensile test (ref. [3])

It is possible to measure the Modulus of Elasticity accurately and precisely with the tensile test provided that the available strip is wide enough to enable taking test samples perpendicular to the rolling direction. For connector manufacturers the strip available is mostly about 10-30 mm wide, therefore it is desirable to be able to do the measurements on small samples, for example 10 mm long. In principle a tensile test could also be done using for example a strip 10-20 mm long, 1 mm wide and 0.15 mm thick. One would need a force of about 50-100 N and would measure a displacement in the range of 50-100 micrometers.

Deriving accurate plastic yielding properties from tensile test data is very circumstantial (ref [2])[*].

2.2. Bend-tests (ref.[4], [5])

The existing bend-tests employ relatively large test strip sizes, 20 mm length or more, depending on material thickness. Measuring far into the plastic range with such large length involves large deflections and is therefore difficult in practice. However, also bend tests lends themselves in principle for miniaturization. For example a 10x10 mm strip can be bent and measured and generate the desired data.

Existing tests deform in one direction, and do not allow for reversing the load for reverse bending experiments. Reversing the load can be of interest in many practical applications, when strip material is bent in one direction during manufacturing and used in the opposite direction in the contact application.

We have tried another alternative bending method, using single prismatic beams as contact springs that are configured with one fixed and one free end. The mechanical load is then applied to the free end. It is easy to control the length of the beam to be short so that yielding occurs at small deflection reducing the problem of large deflections. However the short length poses a problem to the behaviour near the fixation. Loading the free end causes the highest stresses and strains to occur near the fixation, and the fixation itself is adding stress at the same place as well. The effect is that the length needs to be corrected for the compliance in the fixation by adding some estimated length. Another problem at larger displacements is that friction will play a role when slip occurs at the constrained points.

3. The "PD bend-test"

3.1. Instrument and tooling

The instrument used is the DISC (Dutch Instrument for Support in Contact Physics). It has been described before in publications [6] and [7]. The basic setup is shown in Figure 1. The instrument has three moving slides, moved by a DC motor in Y- and Z-direction, and manually in X-direction. Force is built up by moving the Z-slide downwards. The force is increased until a preset level of either force or displacement is reached. The force is measured with a strain-gauge force transducer. Accuracy of force is about 0.01N, of displacement 0.001 mm

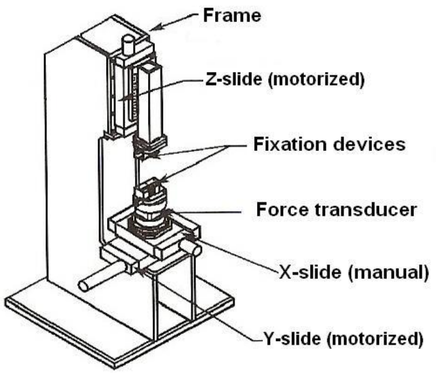

Fig. 1. The DISC instrument

Figure 2 shows the bend-tooling that we have developed and that is mounted on the DISC. A 10x10 mm pad is fixed between two identical mirror shaped blocks. Exactly 4.500 mm away from the fixation is an extension with a small radius which works as a stop and constraints the deflection at the stop to zero. The load is applied at a distance of about 5.5-7.5 mm from the fixation, 1.0 to 3.0 mm from the stop, by an actuator (d in figure 2).

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[*] Sometimes it is questioned whether the Modulus of Elasticity is the same when measured in tensile and in bending modes. It has been found in two independent accurate measurements that the results are the same in tensile and in bending modes. This follows also from the fact that bending stresses are composed of tensile stresses, be it that they vary throughout the cross-section of the spring.

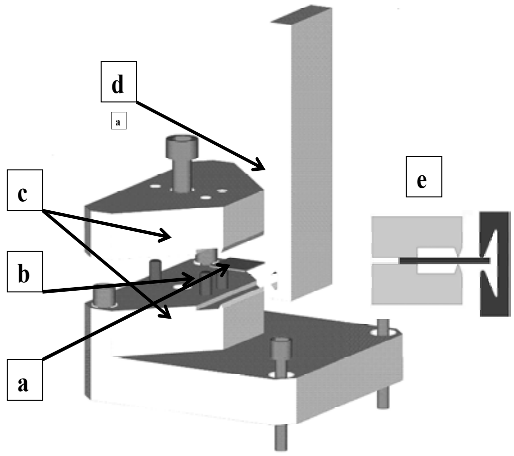

Fig 2. An expanded view of the measurement tooling with the test sample (a) placed against the locator pins (b) and fixed down by the identical contra formal blocks (c). The actuator (d) applies the force downwards or reverse. Drawing (e) shows a cross-section of sample, fixation and actuator

To make test samples a cutting tool, shown in figure 3, has been designed. It enables us to cut 10x10 mm samples out of a strip so that the test samples remain flat, are almost free from burr and have minimal edge stress. Figure 3 also defines what is meant in this paper with the terms parallel and transverse**. If the strip in this picture would be bent down, then we call it parallel because it concerns a spring with its length axis parallel to the rolling direction. It is called transverse when the length axis of the spring is perpendicular to the rolling direction.**

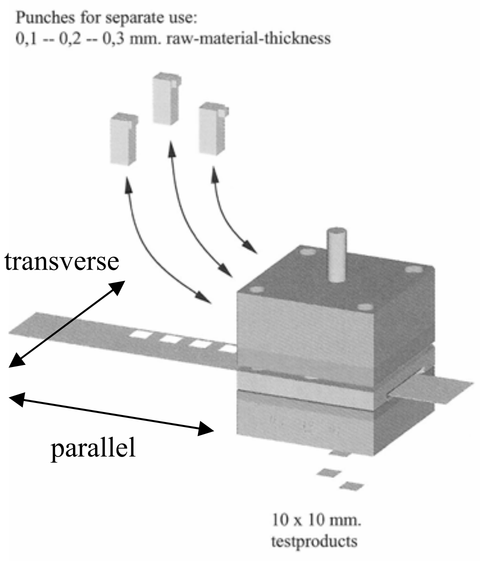

Fig 3. The tool to cut test samples from strip, and the definition of parallel and transverse as measurement orientation.

3.2. The measuring method.

Past experiments with small test strips and reverse bending have brought about the desire for a bending test method with following features:

1. **test sample not larger than 10 mm**
2. **fixation single sided, so that reversing the load is possible**
3. **no high stresses at the point of fixation**
4. **length, width and mounting dimensions accurate enough to enable good accuracy**

Figure 4 explains the mechanical principle of the measurement that we developed: L_1 is the length between fixation and stop, L_2 the length between the stop and the location of the load. T is the material thickness , D the distance that we adjust when adapting the length L_2. P_2 represents the force from the actuator, P_1 is the force at the stop and R and M are the reaction force and moment in the fixation.

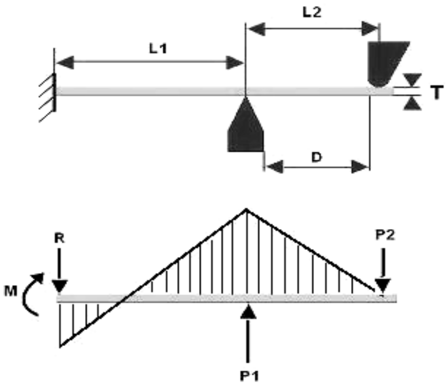

Fig 4. The mechanical principal of the measurement configuration and definition of symbols for lengths and forces.

For the purpose of measuring the modulus of elasticity the load is applied at a distance of 7.5 mm ($L_1 + L_2$) from the fixation. For measuring plastic deformation the distance L_2 is decreased for thinner materials according to the thickness to be measured.

This configuration reduces the stress in the fixation to half the stress at the stop. Therefore, if compared to a situation without stop, the exact location and condition of the fixation is of much lesser influence. The highly stressed area is located symmetrically around the point of the stop.

The formula's, derived for the calculation of the modulus of elasticity and for the force P_1 are based on conventional elastic prismatic beam theory; they are as follows:

$$\{1\} \qquad E = \frac{P_2 * (4 * L_2^{\,3} + 3 * L_1 * L_2^{\,2})}{d * W * T^3}$$

$$P_1 = \frac{3*L_2+2*L_1}{2*L_1}*P_2 \qquad \{2\}$$

With:

E	modulus of elasticity
P_1	force at the point of the stop
P_2	applied force
L_2	distance between fixation and support
L_1	distance between support point and load point
d	deflection at load point
W	sample width (10.00 mm)
T	sample thickness

Distances, sample width and force can be measured with very good accuracy (<< 1%)
The critical measurement is the sample thickness, for example measuring a 0.10 mm thick sample with an accuracy of 1 micrometer leads to 3% inaccuracy due to the third power in the formula {1}.

3.3. The tested Materials

Ten different materials from 3 suppliers have been selected for the measurements, eight of them are copper alloys and two are stainless steel alloys. All materials are customary in the electrical contact industry.
They are listed in table 1 and have been coded A thru J. The materials D and G are Phosphorbronzes (CuSn4), they are supplied by two different suppliers and used also as a reference to previous measurements.
The materials have different thicknesses, the specified and the measured values are also listed in table 1. Because of the difference in thickness it is not possible to directly compare forces and force-deflection curves of the different materials. However, it is made possible to compare the strength and stiffness of the materials through formulas for the modulus of elasticity {1} and formulas for two equivalent stress definitions, {3} and {4}, to be introduced in paragraph 4.

			thickness	thickness
code	Supplier Code	Composition	specified	measured
			mm	mm
A	Stol 76M R580S	Cu Ni1.3 Si0.25	0,200	0,196
B	Stol 78	CuMg0.6	0,147	0,148
C	Stol 94 R750	CuNi2,6Si0.6Sn0.7Zn0.8	0,150	0,151
D	CuSn4	CuSn4	0,200	0,200
E	Argeste 1.4310	X10CrNi18-8	0,100	0,102
F	Argeste 1.4310	X10CrNi18-8	0,140	0,138
G	B14	CuSn4	0,190	0,193
H	K55	Cu Ni3Si0.65Mg0.15	0,190	0,194
I	K57 TM04	CuNi1CoSi	0,150	0,149
J	K88	Cu CrAg Fe Ti Si	0,100	0,100

Table 1. The materials tested and their thickness

4. The measurement results

4.1. The modulus of elasticity

In figure 5 examples of measurement curves are shown for material D, with almost no difference between parallel and transverse direction, and material F where the difference is 16%. All measurements are repeated three times, so the graph shows actually 12 measurement curves. The lines marked FEM shows the resulting curves from finite element analyses with E=133.7 GPa (measured) and E=116 GPa (specified). The slope of these curves must be compared to the steepest curve for material D. in transverse direction.

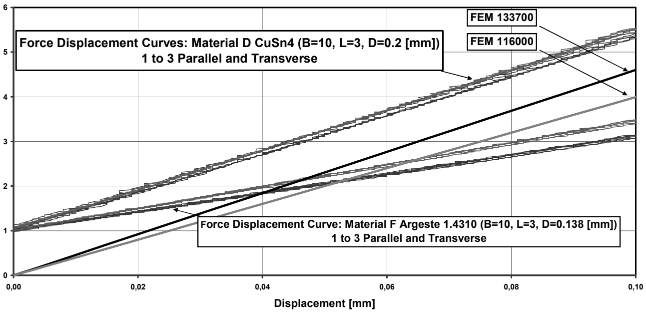

Fig 5. Examples of measured and calculated Force-Displacement curves for 0.200 mm thick Phosphorbronze and 0.138 mm thick Stainless Steel.

Table 2 shows the result for the moduli of elasticity from all measurements, the ratio between the modulus transverse and parallel to the rolling direction, and the supplier specified values. Almost all values are somewhat higher than the supplier specified values, material I forming an exception. This difference between measured and specified values is larger for the transverse direction than for the parallel direction. For materials B, E and F there is a difference of 15-20% between transverse and parallel stiffness.

	E-modulus measured		ratio	E-modulus specified	
material	parallel	transverse	trans/par	parallel	transverse
code	GPa	GPa	%	GPa	GPa
A	139	144	104%	135	135
B	132	157	119%	130	130
C	143	155	108%	132	132
D	129	134	104%	116	116
E	193	224	116%	188	195
F	187	217	116%	182	193
G	131	135	103%	120	120
H	139	142	102%	130	130
I	122	121	99%	131	131
J	142	147	104%	140	140

Table 2. Measured and specified values of the Modulus of Elasticity

4.2. The plastic behaviour and the strength.

Figures 6 and 7 show examples of Force-Displacement curves for materials B (Copper alloy) and E (Steel alloy) measured up to the point where the force reaches a maximum value. The forward curves represent the regular conditions without have been bent on beforehand in the manufacturing process. The strength of material B in this parallel direction is about 30% lower than when the spring has its length axis transverse to the rolling direction!

The grey curves in figures 6 and 7 show the behaviour when the material is bent in the reverse direction, upwards after first having been bent downwards. The difference between forward bending and reverse bending curves, is surprisingly large. As mentioned before, two factors play a role in this plastic deformation. The first is that there is an effect from residual stresses. The second factor is the so-called Bauschinger effect. The strong difference between the behaviour of the copper alloy in comparison to the steel alloy must be due to the Bauschinger effect, because the effect of residual stress should be the same for different materials.

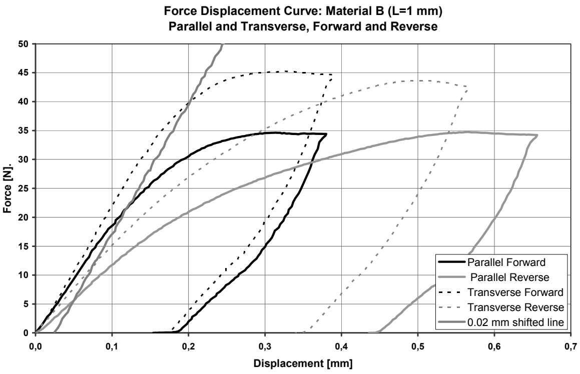

Fig 6. Force-Deflection curves for material B (Copper Alloy). The curves marked “parallel” apply when the spring is formed with its length-axis parallel to the rolling direction.

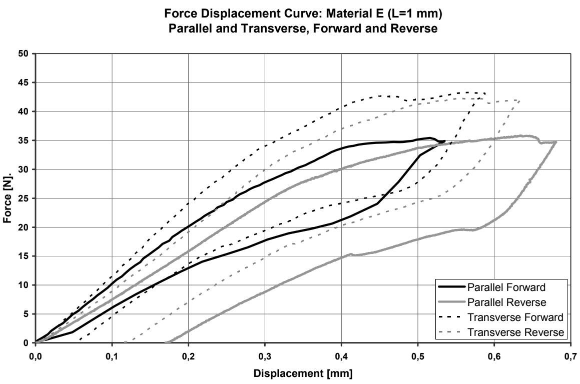

Fig 7. Force-Deflection curves for material E (Steel Alloy)

Figure 8 explains the effect of residual stresses. The originally linear stress pattern (picture a in figure 8) changes during plastic deformation gradually to an almost rectangular form (picture c in figure 8). After unloading there are residual stresses (picture e) and strains (picture f) in the highly loaded region. This is advantageous when loading again in the same direction, the maximum force as measured in figures 6 and 7 can then be reached elastically and the spring has its full potential. When deflecting into the opposite direction the extra stress adds up with the residual stress on the outside, this increases the plastic yield component in the deflection up to the point where the load is again maximal like in picture c of figure 8, but with inverted sign. The maxima of the force and the spring back curves are about equal in forward and reverse bending.

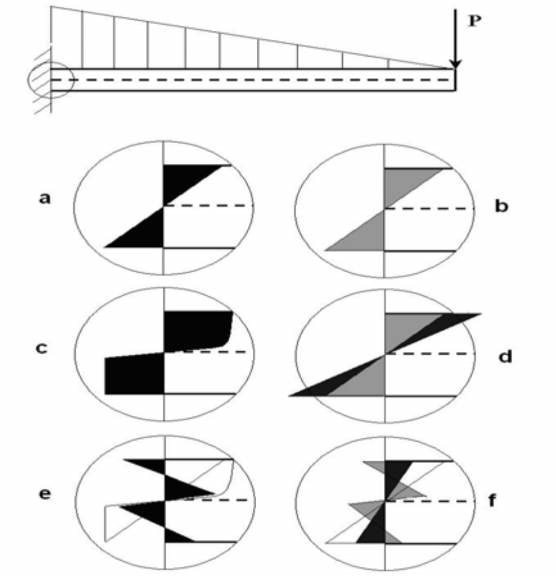

Fig 8. Stress and strain diagrams from a cantilever beam deformed plastically. At the top the distributions of stress (a) and strain (b) during elastic deformation, in the middle stress (c) and strain (d) during plastic deformation and below the distribution of residual stress (e) and residual strain (f) after unloading.

The conventional $\sigma_{0.2}$ value refers to the stress at 0.2 % plastic deformation in the tensile test. The specified values of 534 MPa for material B and 1600 MPa for material E correspond to forces of 19 N and 25 N in figures 6 respectively 7. The effect of the $\sigma_{0.2}$ stress value is not distinguishable in force-deflection curves because the curve remains linear well beyond the force value corresponding to the $\sigma_{0.2}$ value.

Also the strength surpasses the values of σ_{uts} from tensile test measurements, because the σ_{uts} value is influenced by necking, which does not occur in the bending mode.

Two new equivalent stress factors, the $\sigma_{0.02}$ and σ_{pd} are introduced to enable a comparison between materials.

The $\sigma_{0.02}$ value is found by moving the linear part of the force deflection curve 0.02 mm to the right, then determine the force where this line crosses the measurement curve. This is demonstrated in figure 6 where the line intersects the curve at 39 N.

The 0.02 mm distance is chosen because it is assumed small enough to be allowable in most tolerance situations. Assuming that the stress distribution at the crossing point is still elastic (like picture a in figure 8, but it is only approximately true) $\sigma_{0.02}$ can be calculated from the force where line and curve cross with the formula:

$$\{3\} \qquad \sigma_{0.02} = \frac{6 * P_2 * L_2}{W * T^2}$$

The σ_{pd} value is calculated by taking the maximum force from the force-deflection curve, and assume that the stress distribution is rectangular (compare picture c in figure 8). In other words the stress distribution in this model is thought to have a constant positive maximum stress throughout the compression side and the same stress value but negative throughout the tension side; the formula is then:

$$\{4\} \qquad \sigma_{pvd} = \frac{4 * P_2 * L_2}{W * T^2}$$

Table 3 lists the stress values for the different materials. Many supplier specifications do not differentiate between values parallel and transverse to the rolling direction. It appears that there are important differences and also that loading beyond the limits suggested by the figures from the tensile test is very well possible in the bending mode. The most important information for a spring designer is the magnitude of deflection that he can allow without getting too much plastic deformation. With data from the "PD bend-test" he can make the estimates necessary in the conceptual stage using simple elastic formulas from conventional mechanics. Once a concept is generated the designer can use finite element analysis as a verification tool, using the modulus of elasticity measured on the actual strip that he intends to use, including anisotropy. Establishing material data in this way will lead to more accurate predictions in finite element calculations, also for other geometrical configurations than simple prismatic beams and even for plated materials. Figure 9 demonstrates this by comparing the actually measured curve with results from a finite element analysis with the specified σ_y and σ_{uts} values with a second analysis with a bilinear stress-strain curve using the σ_y and σ_{pd} values. The yield stress has been 577 MPa, the modulus of elasticity 133.7 GPa in both analyses

	$\sigma_{0.02}$ forward		$\sigma_{0.2}$	σ_{pd} forward		σ_{uts}
material	parallel	transverse	specified	parallel	transverse	specified
code	MPa	MPa	Mpa	MPa	MPa	Mpa
A	700	880	570	680	730	630
B	760	1130	530	660	870	560
C	1230	1410	700	900	1000	760
D	730	940	580	670	770	630
E	1650	2160	1600	1510	1850	1660
F	1960	2240	1630	1680	1850	1710
G	820	920	580	660	750	610
H	940	1080	660	810	820	750
I	1300	1310	760	950	970	800
J	930	1080	500	720	840	570

Table 3. Measured and specified stress values.

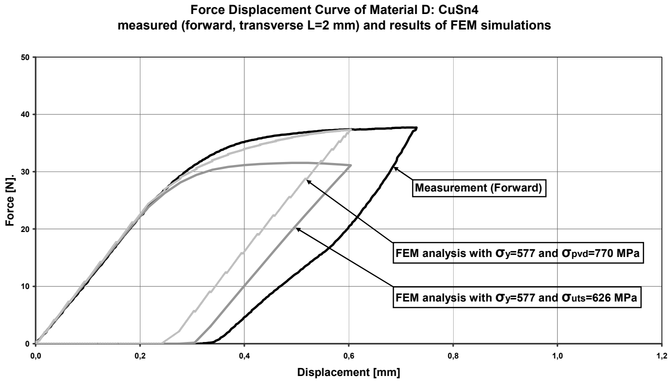

Fig. 9. Comparison between finite element analyses with σ_{pd}=770 and with σ_{uts}=626 and the measured curve.

5. Conclusions

1. **Contact spring members have better spring properties perpendicular to the rolling direction than parallel to the rolling direction for all tested spring materials**

2. **The Bauschinger effect is very strong with copper alloys, reverse bending should be avoided with these materials.**

3. **The Bauschinger effect with the tested steel materials is small if not negligible**

4. **Tensile test values are overly conservative when used for materials in the bending mode.**

5. **The test method should be further improved for very thin materials (T<0.15 mm) by choosing shorter distance between fixation and stop (from 4.5 to 1 mm) and by reducing the radius of the actuator (to 0.1 mm)**

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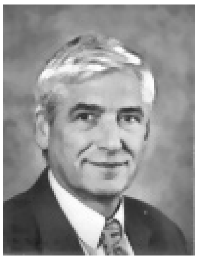

Piet van Dijk received his M.S. degree in Mechanical Engineering from the Eindhoven Technical University in 1971. During 1973-1999, he worked in the AMP European Development Centre (EDC) in ‘s-Hertogenbosch, the Netherlands. In 1999 he founded PVDIJK BV, a consultancy company specialized in the field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