The role of plastic deformation in wear of thin films

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The Role of Plastic Deformation in Wear of Thin Films

A. G. Tangena

P. J. M. Wijnhoven

E. A. Muijderland

Philips Research Laboratories,
5600JA Eindhoven, The Netherlands

The correlation between mechanical stresses and tribological behavior for thin films was studied. A noble metal layer was applied on different substrates. Depending on the thickness of the film and the mechanical properties of the substrate, the wear of the film in a pin-on-plate configuration changed. Using finite element calculations it was shown that the geometry of the system, the mechanical properties of the substrate and the contact load determined the mechanical deformations of the top layer. The calculated von Mises stress averaged over the contact area and the depth of the thin film correlated well with the wear measured. If this average von Mises stress was above the yield stress of the thin film, the wear increased enormously, indicating the importance of plastic deformation in the film. A relatively simple low cycle fatigue model using the Coffin-Manson relation gave a good description of the wear behavior as a function of the average von Mises stress.

Introduction

In a previous paper [1] it was shown that there is a correlation between calculated stresses and wear. In that paper finite element (FE) calculations were performed on a layered electrical contact system as tested by Antler [2]. Comparison of various stresses in the top layer with the wear data from Antler showed that the von Mises stress, averaged over the contact area and the layer thickness correlated very well with these wear data. Below a certain von Mises stress wear was almost negligible. Above this value wear increased sharply. The von Mises stress is accepted as a good criterion for plastic flow and ductile fracture, phenomena that are amongst the basic causes for the formation of wear particles.

In this paper the results of actual wear experiments on layered systems will be compared with FE calculations. The measured wear volume of the gold top layer was correlated with the calculated von Mises stress in that same layer (see also [3]).

Experimental

The Wear Apparatus. The overall design of the pin-on-plate wear apparatus is sketched in Fig. 1. The apparatus was constructed to test wear resistance at relatively low loads. It consisted of a flat plate sliding against a spherical pin. The pin made a linear wear track on the plate. The movement could be either reciprocal or one-way. The normal force, the position of the plate in a horizontal plane (x , y) and the moving velocity were controlled and the normal force, the shear force and the vertical displacement of the pin were measured by a microcomputer. Special programs allowed plots of the actual, the mean values and standard deviations of the measured quantities.

The normal force on the pin was applied by adjusting the current through a coil located in a magnetic field. The part for

applying the normal force was airborne, so that a frictionless vertical movement of the pin was possible. The normal force was measured by a force transducer mounted just above the air bearing. The range of normal forces possible was 100 mN to 5 N. The air bearing was constructed in such a way that rotation of the pin was impossible. The vertical displacement of the pin was monitored by a displacement transducer with an accuracy of 0.02 μm . The plate was moved in a horizontal plane. In the sliding direction an airborne table was constructed. The stroke of this table was 300 mm. The table was driven by a linear displacement unit, containing an optical position measuring device. A dedicated microprocessor controlled the movement of the airborne table. The positioning accuracy obtained with this system was 1 μm . During the experiments the plate was moved in a reciprocal way under the pin with a speed of 1 mm/s and a stroke of 5 mm. One pass consisted of a complete reciprocal motion (two load cycles).

In order to make several adjacent wear tracks on one specimen, a translation stage with an incremental encoder was placed on top of the air bearing. This table permitted a move-

Fig. 1 The overall design of the pin-on-plate wear apparatus. 1. Magnet, 2. Coil for applying the normal force, 3. Normal force transducer, 4. Vertical air bearing, 5. Height transducer, 6. Pin, 7. Plate, 8. Vacuum suction for plate, 9. Shear force transducer, 10. Horizontal air bearing, 11. Translation stage, 12. Air-borne table, 13. Flexible joint, 14. Linear displacement unit, 15. Granite table.

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Table 1 Elastic properties of materials used in the contact system

Material	Young's modulus [N/mm ²]	Poisson ratio
Au	79000	0.42
Ni	193000	0.32
Cu	125000	0.32
Glass	70000	0.25
Steel	210000	0.30

ment perpendicular to the wear track. The stroke of this table was 45 mm with an accuracy of 1 μ m.

The shear force was measured on the plate. For this purpose a small and light table running on aerostatic bearings was constructed, that acted as a carrier for the plate. This table was connected through a force transducer to the translation stage. The plate was attached to the table by vacuum suction and fixed with adjustable clamps.

The entire wear apparatus was placed on top of a damped granite table inside a perspex box. The atmosphere was plain laboratory air.

Measuring the Wear. Wear was measured using a modified profilometer. This profilometer scanned the surface contour or roughness with a diamond stylus with a radius of 2.5 microns. The measuring track was taken over the surface perpendicular to the wear track. Each wear track was measured at two different places. The profilometer was connected to a mainframe computer. A special software package was written using professional plot routines to evaluate roughness data. This package calculated the cross-section and the depth of the wear track.

The wear tracks were also examined with an optical microscope. The width of the track deduced in this way corresponded well with the width measured using the profilometer. The wear of the pin was also checked with this microscope.

Sample Preparation and Characterization. The substrates used in this experiment were made of OFHC-Cu (99.9 percent) or of soda-lime glass (ca. 72 weight percent SiO₂, 13 percent Na₂O, 9 percent CaO, 3 percent MgO, 2 percent Al₂O₃). The size of the Cu substrates was 24 mm $\times$ 27 mm with a thickness of 3.5 mm. These substrates were polished with diamond powder until a roughness R_a of 0.05 μ m was obtained. After this the Cu samples were heat treated at 650 degrees Centigrade for half an hour. In some cases a hard nickel layer was applied on top of this copper substrate. This nickel was applied from a sulphamate bath. The size of the glass substrates was 30 mm $\times$ 30 mm with a thickness of 1 mm. The surface roughness R_a was better than 0.05 μ m. For the Au top layer two different types were used. Both types of gold were of a high purity (99.9 percent, Vickers hardness 70 H_v). The method of application, however, was different. One gold layer was electrodeposited from a citrate-buffered solution. The surface of this gold had a roughness R_a of 1.0 μ m after plating. The second type of gold was applied by evaporation in vacuum. In order to obtain a good adhesion of this gold to the different substrates, a 50 Å Cr layer was first applied. This layer was so thin that its influence on the mechanical stresses in the film was neglected. The surface roughness of the evaporated gold was the same as that of the substrate, namely better than 0.05 μ m. For the pin very smooth balls ($R_a < 0.05 \mu$ m) made of ball-bearing steel SAE 52100 with a hardness of 64 Rockwell C (800 H_v , 30) were used. The materials used in the layered system are supposed to deform not only elastically, but also in a plastic way, implying permanent deformation. To perform reliable model calculations the actual mechanical properties of films and substrates must be known. The mechanical behavior of materials is usually characterized by a

Fig. 2 The plastic part of the true stress-strain curves of pure gold, sulphamate nickel and oxygen-free copper. Through the calculated points an exponential curve is fitted by the least squares method. The yield stresses are also indicated at a strain of 0.002.

true stress-strain curve consisting of an elastic part determined by Young's modulus and a plastic part in which the von Mises stress at which yielding occurs is expressed as a function of the effective strain. Stress-strain curves of bulk materials are normally measured in a uniaxial tensile strength test. In the case of a thin film, this test is extremely difficult. Therefore we have applied an alternative method to obtain the stress-strain curves for films and substrates. The elastic properties were obtained from the values of the bulk materials, since these properties are not changed much by small alloying additions, heat treatment or not too severe cold-work [4]. The elastic properties of the materials used are indicated in Table 1. The plastic part of the stress-strain curve was deduced from a quasi-static indentation test [5, 6] using:

$$\sigma_f \approx \frac{p_m}{C} \quad \text{and} \quad \epsilon \approx 0.2 \frac{d}{D}$$

where σ_f is the flowstress, p_m the mean contact pressure, C a constraint factor, which equals 3 for indentation with a spherical ball, ϵ the true strain, d the diameter of indentation and D the diameter of the indenter.

A Vickers hardness number H_v gave the yield stress σ_0 [7]:

$$\sigma_0 \approx \frac{H_v}{3} (0.1)^n$$

where n is the strain-hardening coefficient.

Stress-strain curves for the OFHC-Cu substrate, the sulphamate nickel and the pure galvanic gold are presented in Fig. 2. The mechanical properties of the evaporated coating were tested in the ultramicrohardness tester [8]. As the mechanical properties of both golds proved to be virtually the same, it was considered sufficient to do calculations for one type of gold only. The yield stresses of the glass substrate and the steel ball were sufficiently high (glass H_v 450, steel H_v 800), so that only their elastic properties were taken into account in the calculations. The electrodeposited samples and the balls were cleaned in a freon-vapor degreaser before being used in the experiment. The samples with evaporated gold were used as obtained.

Finite Element Calculation. The program we used was the MARC finite element program (by MARC Analysis Research Corporation [9]).

In this program indentation bodies (pins) are assumed to be rigid, whereas the layered substrate has elastoplastic properties. This means that in order to closely match the calculated stresses with the actual stresses occurring in the experiment we must approximate this situation as close as possible. Therefore a pin with a large hardness was chosen (800 H_v , 30), so that for a soft layered system the pin appears rigid. In the case of the hard glass substrate we compensated for the elastic deformation of the pin by taking an effective radius of 1.32 times the

Fig. 3 The axisymmetric mesh used for elastic-plastic calculations of indentations of layered systems. Indicated sizes are in microns.

Fig. 4 The von Mises stress in the top gold layer as a function of the radial position for an axisymmetric layered system consisting of a 3.0 μm gold layer on a soft copper substrate indented by a rigid sphere with a radius of 4 mm. The stresses are shown for a normal force of 0.5, 1.5, 2.5, and 4 N.

actual indenter radius (see Timoshenko [10]). In the program indenters are represented by so-called gap elements that connect the material points of the gold surface to the centre point of the indenter (see Fig. 3). These gap elements simulate a frictionless contact between the indenter and the material surface, once the gap is locally closed.

The solid elements modelling the layered system were quadrilateral 4-node axisymmetric elements with an isotropic hardening model (see Table 1 and Fig. 2 for their mechanical properties).

We approximated the stress field under a sliding pin with an axisymmetric indentation. The friction coefficient in these experiments was approximately 0.1. In that case the stress field for a pure frictionless indentation will not differ too much from the sliding situation (see also [11]). The finite element mesh used in the calculation possessed a cylindrical symmetry (see Fig. 3). The width of the contact area was chosen as 150 μm and the total width of the mesh as 300 μm , since outside the contact area the stresses fall off rapidly. 65 gap elements were used, spaced 2.34 μm apart. The gold top layer was represented by 132 elements in two layers. The substrate was represented by 396 elements. Altogether 593 elements were used to model the contact situation. The total thickness of the mesh was 507 μm . The lower side of the mesh was fixed, while the outside and the upper side of the mesh outside the contact area were left free.

The normal force on the indenter was prescribed in the calculations.

In reference [1] it was shown that the von Mises stress,

Fig. 5 The von Mises stress averaged over the depth of the gold layer as a function of the radial position for an axisymmetric layered system indented by a rigid sphere with a radius of 12.5 mm at a normal load of 4 N. The layered system consists of a 3.0 μm gold film on a soft copper substrate with and without a hard nickel intermediate layer and a hard glass substrate.

averaged over the contact area and the depth of the layer, correlated best with actual wear experiments. The results from the present experiments were therefore evaluated in terms of this stress.

Results

Finite Element Calculations. We have evaluated the stresses in the gold layer, since wear is initially occurring in the top layer. The variation of the von Mises stress over the depth is known in four integration points, but since the layers are thin compared to the size of the contact area and the stresses do not vary much over the depth of the layer (<25 percent variation), we will use only stresses averaged over the depth of the gold layer. In Table 2 the contact radii and the calculated von-Mises stresses averaged over the depth as well as over the contact radius are presented for the contact situations calculated: four different loads, four different radii of the pin, three substrates and two layer thicknesses for the gold. We will not discuss all these situations separately, but we will indicate the influence of important parameters in Figs. 4 to 7. Vertical bars in these figures indicate contact radii, whereas the horizontal solid line at 114 N/mm² indicates the yield stress of the gold.

As a rule the von Mises stresses in the gold film increased with an increase in the normal load (see Fig. 4). We note that the stress regime in the gold layer can change from a purely elastic one to a plastic one. In the case of an elastically deforming gold layer the maximum von Mises stresses are found at the edge of the contact zone.

The substrate strongly influences the stresses in the gold layer. Figure 5 shows the von Mises stresses averaged over the depth of the gold layer for different substrates. We note that with a soft copper substrate the stresses as well as the contact radius are large. The use of a hard nickel intermediate layer reduces the stresses, particularly in the center of the contact. The system with the hard nickel layer has slightly smaller contact radii than the system without this layer. The hard glass substrate reduces the contact area considerably, it differs only slightly from the Hertz contact area for the steel pin-glass substrate system, Figure 5 indicates that for this substrate the von Mises stress is low in the entire contact. All systems have larger stresses on the edge of the contact area.

Figure 6 shows how the stresses inside the film are influenced by the radius of the indenter for a gold layer on a copper substrate. As a rule the contact radius increases slightly and the von Mises stress averaged over the contact area decreases with increasing indenter radius.

The influence of the thickness of the gold was investigated

Fig. 6 The von Mises stress averaged over the depth of the gold layer as a function of the radial position for an axisymmetric layered system consisting of a 3.0 μm gold layer on a soft copper substrate indented by a rigid sphere at a normal load of 1.5 N. The radius of the indenter is 2.5, 4.0, 5.0 and 12.5 mm.

Fig. 7 The von Mises stress averaged over the depth of the gold layer as a function of the radial position for an axisymmetric layered system indented by a rigid sphere with a radius of 2.5 mm at a normal load of 2.5 N. The stresses are shown for a 1.0 and a 3.0 μm gold film on a glass substrate.

Fig. 8 The shape of the wear scar after 1 pass (8.a) and 250 passes for an elastically deforming (8.b) and an elastic plastically deforming Au layer (8.c) on a plastically deforming Cu substrate

for a 1.0 and a 3.0 μm thick gold layer on a glass substrate. Figure 7 shows that there is a reduction in the von Mises stresses in the layer for the thicker gold. This is understandable if we consider that in these circumstances the gold layer and the glass substrate remain elastic. In such a case the gold layer is not softer; on the contrary, the gold layer has a higher Young's modulus than the glass substrate. Thus in effect the system has a stiffer layer on a softer substrate. The thicker this layer, the smaller the stresses will be.

Wear Experiments. In the wear experiments two types of pure gold were examined. A pure gold layer applied by evaporation was tested with a soft copper and a hard glass

Table 2 Calculated and experimental results for layered systems tested. Shown are the calculated radius, the von Mises stress (averaged over the contact radius and the depth of the gold layer) and the cross-section of the wear track (difference between 1 and 250 passes).

Radius pin [mm]	Au layer [μm]	Ni layer [μm]	Substrate	Normal load [N]	Contact radius [μm]	v. Mises stress [MPa]	Wear evaporated Au [μm²]	Wear el.deposited Au [μm²]
2.5	3.0	0.0	Cu	0.5	28	75	20	51
2.5	3.0	0.0	Cu	1.5	68	118	110	185
2.5	3.0	0.0	Cu	2.5	87	122	299	289
2.5	3.0	0.0	Cu	4.0	113	129	689	679
2.5	3.0	4.0	Cu	0.5	33	77		24
2.5	3.0	4.0	Cu	1.5	59	78		102
2.5	3.0	4.0	Cu	2.5	77	106		181
2.5	3.0	4.0	Cu	4.0	98	120		428
2.5	3.0	4.0	Cu	0.5	38	64	63	
4.0	3.0	0.0	Cu	0.5	66	110	123	
4.0	3.0	0.0	Cu	1.5	87	117	300	
4.0	3.0	0.0	Cu	2.5	87	117	528	
4.0	3.0	0.0	Cu	4.0	113	122	528	
5.0	3.0	0.0	Cu	0.5	40	59	17	0
5.0	3.0	0.0	Cu	1.5	66	104	98	80
5.0	3.0	0.0	Cu	2.5	87	114	199	130
5.0	3.0	0.0	Cu	4.0	110	118	402	221
5.0	3.0	4.0	Cu	0.5	35	38		2
5.0	3.0	4.0	Cu	1.5	63	47		39
5.0	3.0	4.0	Cu	2.5	82	74		91
5.0	3.0	4.0	Cu	4.0	103	100		172
5.0	3.0	4.0	Cu	0.5	45	34	22	38
12.5	3.0	0.0	Cu	0.5	73	59	78	33
12.5	3.0	0.0	Cu	1.5	91	80	140	71
12.5	3.0	0.0	Cu	2.5	91	80	174	127
12.5	3.0	0.0	Cu	4.0	117	101		12
12.5	3.0	4.0	Cu	0.5	42	19		15
12.5	3.0	4.0	Cu	1.5	70	34		30
12.5	3.0	4.0	Cu	2.5	89	46		64
12.5	3.0	4.0	Cu	4.0	113	60		
2.5	3.0	0.0	glass	0.5	23	56	9	
2.5	3.0	0.0	glass	1.5	35	56	25	
2.5	3.0	0.0	glass	2.5	40	55	38	
2.5	3.0	0.0	glass	4.0	47	63	77	
2.5	1.0	0.0	glass	0.5	23	42	7	
2.5	1.0	0.0	glass	1.5	35	69	13	
2.5	1.0	0.0	glass	2.5	42	86	25	
2.5	1.0	0.0	glass	4.0	49	101	55	
12.5	3.0	0.0	glass	0.5	40	12	8	
12.5	3.0	0.0	glass	1.5	59	20	19	
12.5	3.0	0.0	glass	2.5	70	26	27	
12.5	3.0	0.0	glass	4.0	82	32	46	
12.5	1.0	0.0	glass	0.5	42	18	6	
12.5	1.0	0.0	glass	1.5	61	29	12	
12.5	1.0	0.0	glass	2.5	73	35	19	
12.5	1.0	0.0	glass	4.0	84	42	24	

substrate, while a galvanic gold layer on a copper substrate was tested with and without a hard nickel layer in between the gold and the copper. The wear experiments were performed with several different radii of the indenter at four different loads (see Table 2). Altogether this resulted in 32 different contact situations for the evaporated gold and 24 different situations for the galvanic gold.

In these situations the wear of the pins and transfer of metal to the pin was negligible as established with an optical microscope.

An evaluation of the wear results of the layered system proved to be rather difficult for several reasons. One difficulty arose from the use of non-wearing spherical pins. This meant that when the gold layer was wearing, the contact area was increasing. When the contact area reached a certain size wear would cease. This situation was reached after approximately 250 wear cycles. A second difficulty arose with the soft copper substrates. It was caused by the fact that even in the case of an elastically deforming gold layer, the substrate was plastically deforming and a groove was formed. In the profilometer scans or with the optical microscope it is not possible to distinguish between a groove caused by plastic deformation of the substrate and one caused by wear of the gold layer. There is however one crucial difference between the two mechanisms (see Fig. 8). Plastic deformation of the substrate takes place during the first wear pass, while wear of the gold layer is a more slowly developing process. When the Au layer is elastically deforming no increase in wear scar is found during successive passes. For a plastically deforming layer the wear scar does increase with the number of passes.

Since after approximately 250 passes the size of the groove is stabilized, we evaluated the wear of the gold film by comparing the cross-section of the track after 1 and 250 passes. This difference in cross-section between 250 passes and 1 pass is mentioned in Table 2 as wear cross-section.

The wear tracks in the gold layer on the glass substrate

could only be observed after a sufficiently large number of wear passes. In these cases the size of the wear scar was only slightly larger than the size of the contact radius, as one would expect from elastic Hertz theory, indicating that wear was practically at a zero level.

In none of the experimental situations was the gold layer worn through. The size of the wear scar was reproducible to within 10 percent, therefore it was considered sufficient to test every contact situation twice. The wear tracks showed a grooved pattern, indicating an abrasive wear mechanism, where small wear particles groove the surface. Small wear particles were deposited at the edge of the track, where the direction of motion was reversed. For the experiments with the copper substrate with and without the nickel intermediate layer, the depth of the wear track was the depth corresponding to the radius of the indenter, since the indenter was sufficiently rigid compared to the layered system. The depth for the systems with a glass substrate was equal to the depth corresponding to the depth of the effective radius in the contact as obtained from elastic theory.

From Table 2 we note that the wear of the gold film increased with normal load.

The substrate strongly influenced the wear of the gold film. A soft copper substrate caused extensive wear. The use of a hard intermediate Ni layer between the copper substrate and the gold layer reduced wear compared with the system without this layer. A hard glass substrate reduced wear considerably.

The radius of the indenter also had great influence on the wear of the gold layer. The smaller the indenter radius, the larger the wear. The larger radii gave a larger width of the wear track, but the cross-section of the groove was smaller.

The thickness of the gold layer had little influence on the wear results. We note from Table 2 that wear was somewhat greater for the thicker (3.0 μm) gold layer.

Both types of pure gold, the evaporated and the galvanic gold showed roughly the same trends in wear results. Because of their roughness, the wear of galvanic layers was more difficult to evaluate than the wear of the smooth evaporated ones. This was especially the case for the elastically deforming layers.

Discussion

Figures 9 and 10 show the correlation between wear and stresses for the evaporated and the galvanic gold layer. The results of the wear tests are related to the calculated von Mises stress averaged over the depth of the gold layer and the contact radius. In these figures the normal load (0.5, 1.5, 2.5, 4.0 N) is not indicated with a special marker, so for every contact configuration there are four identical markers. The influence of the normal force can be deduced from the increase of the von Mises stress for identical markers (see Table 2). The vertical solid line at a von Mises stress of 114 N/mm^2 denotes the yield stress of the gold. We note that there is a strong correlation between the von Mises stresses in the gold layer and the wear occurring in this layer. When the average von Mises stress reaches the yield stress and the entire gold layer is plastically deforming, wear increases enormously. The influence of the normal load, the substrates and the different pin radii on the wear process is quite well described by the influence of these parameters on the von Mises stresses in the gold layer.

It is remarkable that all 32 different contact situations described in Table 2 seem to fit on a single curve in Fig. 9. Further on we will show a theoretical model how to obtain this curve. For the 1.0 and 3.0 μm thick gold layers on glass the von Mises stress is lower for the 3.0 μm layer, whereas the wear for this layer is somewhat larger. However, we note from Fig. 9 that these points fall within the narrow range of experimental points.

Figure 10 shows that for the electrodeposited gold the same

Fig. 9 Wear data on an evaporated gold layer plotted against the von Mises stress averaged over the contact width and the depth of the gold layer for 32 different contact situations. Parameters are the indenter radius R_{ind} , the Au thickness t_{Au} and the substrate. The solid line is obtained from a low cycle fatigue wear model.

Fig. 10 Wear data on an electrodeposited gold layer plotted against the von Mises stress averaged over the contact width and the depth of the gold layer for 24 different contact situations. Parameters are the indenter radius R_{ind} and the Ni thickness t_{Ni} . The solid line is obtained from a low cycle fatigue wear model.

shape of the curve and even a quantitative agreement with Fig. 9 is found. In this figure we note that at a certain von Mises stress the wear results of the system with an intermediate layer are always larger than those of the system without the layer. This is the result of choosing a von Mises stress averaged over the contact area as well as the depth as the representative stress in the contact situation. Such an average stress tends to underestimate the stresses occurring in the gold layers on the harder substrates, because for these substrates the largest stresses are at the edge of the contact (see Fig. 5).

In this paper wear was correlated with a von Mises stress averaged over the contact area and the depth of a thin layer. Since the von Mises stress is a distortion energy criterion, this means that the deformation energy is the important parameter controlling this wear process. So the general trend found in reference [1], namely that plastic deformation is a very important parameter in wear, is more firmly established.

We found in the experiments that wear ceased after approximately 250 passes. This is to be expected, since an increase of contact area will eventually lead to elastic deformation of the gold layer.

Wear involves primarily cyclic plastic deformation, crack nucleation and crack propagation. Because of the similarity between the wear process and low cycle fatigue we assume that for the wear process a formulation analogous to the Coffin-Manson law can be used [12]. The number of passes N to form a wear particle and the cyclic plastic strain range $\Delta\epsilon_p$ are then related as follows:

$$\Delta\epsilon_p N^b = \epsilon_c = \text{constant} \quad (1)$$

where b is a constant whose value is approximately 0.5 and ϵ_c some critical strain necessary to generate a wear particle.

Equation (1) implies that whenever the number of passes n is larger than the number N necessary for the formation of a wear particle the system will show wear. The exact value of ϵ_c in equation (1) is not known, but from the experiments we note that our number of passes (250) is sufficient to generate wear particles, so that N is smaller than 250. We assume that the wear volume is proportional to the number of passes divided by the critical number of passes. We then obtain the following formulation for the wear volume per unit sliding distance W :

$$W = k_1 V \frac{n}{N} \quad (2)$$

where k_1 is an arbitrary wear constant and V the plastically deformed volume. Combining (1) and (2) yields:

$$W = k_1 V n \left[\frac{\Delta \epsilon_p}{\epsilon_c} \right]^{\frac{1}{b}} \quad (3)$$

The plastic strain range $\Delta \epsilon_p$ changes with the number of cycles, since in the wear process the contact area grows until eventually all deformations are elastic and no wear particles are generated any more. In such a case we should use a linear cumulative damage rule (Miner's rule, see Dieter [12]). But since we do not know the exact value of the plastic strain range during the 250 wear passes, we will use the value for the first cycle as an approximation.

The plastic strain range $\Delta \epsilon_p$ and the applied von Mises stress $\bar{\sigma}$ are correlated through the cyclic stress-strain curve [13]:

$$\bar{\sigma} = K' \Delta \epsilon_p^{n'} \quad (4)$$

where n' is the cyclic strain-hardening coefficient and K' a constant. The values of K' and n' are not known exactly, since they depend on the number of cycles. n' will change from some initial strain hardening coefficient to a value between 0.1 and 0.2 for most metals [13]. Since the number of cycles is relatively low in these experiments we will approximate n' with the value, obtained from Fig. 2, namely 0.31.

Combining equations (3) and (4) we finally obtain for the wear volume per unit sliding distance:

$$W = k_1 V n \epsilon_c^{-\frac{1}{b}} \left[\frac{\bar{\sigma}}{K'} \right]^{\frac{1}{bn'}} = k_2 V \bar{\sigma}^{\frac{1}{bn'}} \quad (5)$$

With $b = 0.5$ and $n' = 0.31$ we note that the wear volume per unit sliding distance is proportional to the von Mises stress to the power of 6.45. If during the cyclic deformation process the value of n' changes to a value between 0.1 and 0.2 (according to [13]) this value of 6.45 might become twice as large. The large value of this power indicates that the von Mises stress is extremely dominant in equation (5) and thus also in the wear process. In a layered system the volume of deformed material V is proportional to $a^2 \times d$ or a^3 if the substrate also deforms, where a is the contact radius and d the thickness of the layer. From Table 2 we note that it is possible to have different values of the contact radius a at the same von Mises stress. In other words there is no simple relation between the average von Mises stress and the contact radius. The von Mises stress to the power of 6.45, however, is extremely dominant compared with the volume of deformed material V . So for simplicity we take V as a constant. In this way we can construct a theoretical curve for the dependence of the wear cross-section (wear volume per unit sliding distance) on the average von Mises stress. In Figs. 9 and 10 this theoretical cross-section is represented by solid lines. The proportionality constant $k_2 \times V$ was taken as $1.5 \cdot 10^{-11} \text{ [N/mm}^2\text{]}^{-6.45} [\mu\text{m}^2]$. This value is small mainly because K' in equation (5) is large. The theoretical model does not predict a sharp wear-no wear transition, but a more gradual transition from a low wearing regime at a low average von Mises stress into a severe wearing regime, when the layer is completely plastically deforming. We

note that the theoretical curve predicts low or no wear at all for average von Mises stresses much lower than the yield stress (114 N/mm^2). In this region it is possible that the number of passes n is smaller than the number N necessary to form a wear particle (see equation (1)).

The experimental wear results of Figs. 9 and 10 show the relative unimportance of the deformed volume. In these figures the wear cross-section is plotted against the average von Mises stress. The deformed volume was not taken into account. Incorporating this volume by plotting the wear cross-section W divided by the deformed volume V as a function of the average von Mises stress did not show a better correlation than was found in Figs. 9 and 10. It is possible that the influence of the deformed volume is masked by the gradually changing stress state during the 250 passes.

The good correlation of the simple wear model with the experimental results indicates that low cycle fatigue could be an important parameter in the wear mechanism.

In this paper we did not go into the actual wear mechanism too deeply. In fact we calculated a macroscopic stress field and did not take microscopic effects into account. A more refined wear model should take the microscopic stress fields from wear particles or surface asperities as well as the macroscopic stress field into account. We note that at low von Mises stresses, the actual wear of the layered system is somewhat larger than the fatigue model predicts. This could be due to ploughing of asperities, so that the stress field from asperities or wear particles is interfering with the macroscopic stress field. Such a mechanism would also result in a more gradual transition from the mild to the severe regime.

A remarkable result is that evaporated and electrodeposited gold show the same dependence of wear on the average von Mises stress. Of course the material properties are virtually the same. The roughness, however, varies widely. According to the elastic contact theory of Greenwood [14] the contact roughness can have a large influence on contact stresses. Our experimental results show that this contact theory is not directly applicable to the situation studied. Several reasons may be responsible for this. In the experiments with the galvanic gold the size of the contact is predominantly determined by the deformation of the copper substrate and not by deformation of the asperities on the gold layer. This means that the influence of the roughness on the contact parameters is relatively small. If the surface is also plastically deforming, the influence of the surface asperities on the contact parameters is considerably reduced.

In the case of a hard substrate the maximum of the von Mises stress in the layer shifted towards the outside of the contact region (see Fig. 5), so that the stresses can be large outside the contact area, where they do not contribute to the average von Mises stress. It might be desirable to change the stress criterion for such systems so as to include these stresses.

A problem occurring with thicker layers or even solid materials is to what depth it is necessary to take account of the stresses.

Since we know the local von Mises stress it might be possible to describe the local wear rate in the contact area. Such an approach could be useful if the contact area consisted of different materials.

In the literature several other criteria are mentioned that separate a mild and severe form of wear.

One of the first is attributed to Burwell [15]. He stated that in his experiment there was a transition from mild to severe wear when the normal stress on a steel surface exceeded $10 \cdot 10^6 \text{ gr/cm}^2$. This value was only slightly larger than one third of the indentation hardness ($H_B/3 = 7.410^6 \text{ gr/cm}^2$).

K. L. Johnson [16] indicated that in a contact situation as used by Burwell first yield occurs at a normal stress of 1.6 times the yield stress. The contact is in the fully plastic state for a normal stress 3 times the yield stress. This means that in

Burwell's contact geometry the system starts to yield at a normal stress of $8 \cdot 10^6$ gr/cm², while fully plastic deformation occurs at $15.3 \cdot 10^6$ gr/cm². This indicates that plastic deformation might be the critical parameter in Burwell's experiments too.

In the zero-wear model [17] a shear stress on the surface is used as the criterion for wear-no wear situations. In the appendix we show that rewriting the basic formulations of this model leads to a formulation analogous to equation (5), showing the usefulness of the approach presented.

In this paper perfect adhesion between layer and substrate was assumed. If, however, the layer detaches during the wear process this might contribute significantly to the wear volume.

Conclusions

It was possible to approximate the stresses in an experimental contact situation, where hard pins with different radii were sliding against a layered system consisting of a gold layer on different substrates, using an axisymmetric indentation.

The wear data of these contact situations correlated well with the von Mises stress averaged over the depth and the contact radius of the gold layer. If this stress showed that the gold layer was completely plastically deforming, the wear of the gold layer increased dramatically. The influence of the normal force, the substrate and the radius of the indenter on the wear of the gold layer could be described.

The wear results did not depend much on the way the pure gold layer was applied. Evaporated and electrodeposited gold films showed the same dependence of wear on the average von Mises stress.

The surface roughness of the gold layer did not show great influence on the wear results.

It was possible to describe the wear results rather accurately using a low cycle fatigue model. This theoretical model showed the importance of the von Mises stress in the wear process.

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APPENDIX

Comparison Between Zero Wear Model and Low Cycle Fatigue Model as Presented in the Paper

The zero-wear theory [17] states that wear can be controlled by limiting the maximum shear stress $\tau_{\max}$ occurring in the contact zone. More specifically: the average depth of the wear scar is less than or equal to one half of the peak-to-peak value of the surface roughness of the coarser surface for n passes if the shear stress $\tau_{\max}$ is smaller than or equal to:

$$\tau_{\max} \leq \left[\frac{2000}{n} \right]^{\frac{1}{9}} \gamma_R \tau_y \quad (\text{A.1})$$

where γ_R is a constant depending on the lubrication regime and τ_y the yield point in shear.

This implies that if we impose a shear stress $\tau_{\max}$ on the surface, the wear depth will be roughly equal to half the surface roughness. Say the wear volume is equal to V_0 in n passes. This means that the wear per cycle V_c will be equal to:

$$V_c = \frac{V_0}{n} \quad (\text{A.2})$$

Substituting equation (A.2) in equation (A.1) yields:

$$\tau_{\max} = \left[\frac{2000}{V_0} V_c \right]^{\frac{1}{9}} \gamma_R \tau_y \quad (\text{A.3})$$

rearranging equation (A.3):

$$V_c = \frac{V_0}{2000(\gamma_R \tau_y)^9} \tau_{\max}^9 = k_z V_0 \tau_{\max}^9 \quad (\text{A.4})$$

The maximum shear stress criterion is a Tresca type of criterion. The Tresca criterion is very similar to a von Mises criterion (maximum difference ca. 15 percent). Therefore we approximate the $\tau_{\max}$ of equation (A.4) by the von Mises stress $\bar{\sigma}$. We then obtain:

$$V_c = k_z V_0 \bar{\sigma}^9 \quad (\text{A.5})$$

Now if we compare equation (A.5) with equation (5) we note the similarity. The value of $1/bn'$ in equation (5) is 6.45, whereas in equation (A.5) the power of the von Mises stress $\bar{\sigma}$ has a value of 9. To explain this difference we have to look at $1/bn'$, where b is a fatigue constant and n' a material deformation constant. For the gold tested the value of n' was 0.31. For most materials the value of n' will be between 0.1 and 0.2, so that for different materials a value of 9 for the power of the von Mises stress $\bar{\sigma}$ represents a realistic value.