The mechanism of metal transfer in sliding friction

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THE MECHANISM OF METAL TRANSFER IN SLIDING FRICTION

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SUMMARY

Accurate observation of the wear process during dry sliding leads to the conclusion that metal transfer always occurs according to the same fundamental process. Depending on circumstances there is only a difference in scale, on which the process presents itself.

The fundamental mechanism of transfer can be described on the basis of a model that is a refinement of Cocks and Antler's description of prow formation. This model, in which deformation and crack formation are essential elements, enables one to elucidate the role of several factors influencing the transfer process (work hardening, roughness, environment, etc). This will be illustrated by the sliding couple of two plain carbon steels.

1. INTRODUCTION

The adhesive wear process is generally considered to be characterized by the generation and rupture of junctions between running surfaces, resisting slip in the real area of contact more or less effectively through atomic forces. Based on this concept, laws of wear have been formulated and the influence of various factors on the wear process have been dealt with. Recently a calculation of friction was published. However, it is evident that the classical model only roughly approaches the development of a strong junction. Cocks and Antler considered the process of prow formation by which contact is maintained for a longer period while the junction is growing and the junction base is moving along one or both of the running surfaces. Besides prow formation, some other types of adhesive wear were distinguished. Conditions and details in relation to transfer through prow formation and allied forces are found in ref. 13. A general model for adhesive contact development, however, does not seem to be available.

This paper contributes to the insight into the proceedings on a micro scale through detailed research of the severe wear process in a wide field of experimental circumstances and assists the prediction of the influence of various factors on the process with the help of a model.

2. EXPERIMENTAL PROCEDURE

2.1 Apparatus

The experiments were carried out on two pin/ring machines, one for very...
Fig. 1. Wear ($w$) and coefficient of friction ($f$) as a function of sliding distance ($s$) for annealed plain carbon steel specimen in argon and oxygen respectively (schematic representation for load 50 N and sliding velocity 0.5 m/s). Figures in the $w/s$ diagram refer to the photomicrographs, e.g. Fig. 1.1 shows a detail of the ring surface at the moment "1" in stage A.
slow and the other for higher speeds. Test specimens contained in a controlled atmosphere (approx. 50 mm WC gauge) were run unlubricated. At low speed the pin was loaded prior to rotation of the ring (standing start), at higher speed loading followed rotation (flying start). The displacement of the pin, frictional force, normal load, temperature 5 mm under the running surface of the pin and transitional resistance (during some tests) were continuously recorded. Percentages of oxygen and water vapour were measured intermittently.

2.2. Test specimens

Rings (diameter 82 mm, width 15 mm) and pins (running surface 8 × 2 mm\(^2\), over-all length in sliding direction) were of annealed carbon steel with 0.43 and 0.57% C respectively. Many other pin materials have been tested.

The rings were ground circumferentially (transversal roughness approx. 8 ru c.l.a.), followed by treatment with 400 and 600 grade abrasive paper on the test machine (5 ru c.l.a.). The pins, after milling to the desired radius were finally adjusted to the ring by grinding with 320 and 600 grade paper attached to a dummy ring. Specimens were cleaned with alcohol. For each experiment a new pin and a fresh ring track were used.

3. EXPERIMENTAL RESULTS

3.1. Steel against steel

From Fig. 1 it is obvious that in the development of the coefficient of friction \(f\), and the pin position \(w\), during the test, two or three periods can be distinguished, viz. incubation period (A), severe wear (B\(_1\) and B\(_2\)) and occasionally mild wear (C). Table I gives a survey of characteristic phenomena in periods A and B, together with the effect of the variation of several parameters (sliding speed, oxygen pressure, topography, sliding distance and load). The process will be discussed extensively in ref. 14.

3.1.1. Incubation period A

In this period the pin position does not change, the coefficient of friction is low and increasing (0.2–0.4) and the running surfaces are hardly affected. A mild grooving process seems to become active (Fig. 1.1), at the end of the incubation period changing into adhesive damage. The sliding distance during incubation is greatly dependent on sliding speed, load and topography (especially of the ring surface) and to a lesser degree on oxygen pressure. Grooves made transverse to the direction of sliding (abrasive paper 320) caused a prolongation of this distance with partial slight adhesion.

3.1.2. Severe wear B\(_1\) and B\(_2\)

During the running-in process, B\(_1\), the pin moves away from the ring and friction attains high values. Pin position and the coefficient of friction fluctuate considerably with clear interrelation. Grooves emerge into the running surfaces, often with sills (Figs 1.2 and 1.3.) as found in mechanical machining\(^{15}\), and a piled up particle at the end, mainly built up from material originating from a groove in the mating surface\(^{16}\). These particles have a well-known prow\(^{5-13}\) and are pre-
**TABLE I**

**CHARACTERISTIC PHENOMENA IN THE DRY SLIDING WEAR PROCESS OF STEEL 1045 AGAINST ITSELF AND THE INFLUENCE OF SEVERAL PARAMETERS** (*A* = incubation period, *B* = severe wear period, cf. Fig. 1)

<table>
<thead>
<tr>
<th>Process period</th>
<th>A</th>
<th>B₁</th>
<th>B₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic phenomena</td>
<td>mild scratching of running surfaces; no wear debris; $f$ (coeff. of friction) low; $w$ (pin position) constant</td>
<td>formation of coarse prows on &quot;fresh&quot; surfaces; coarse and finer metallic debris; $f$ and $w$ fluctuating considerably, $f=0.2-1.5$; $w \leq 0$</td>
<td>formation of prows on rough and strain hardened surfaces; coarse, fine and very fine metallic debris; $f = 0.6-0.8$; $(dw/ds)_n$ = constant. band width $\Delta w = 20-50 \mu m$.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect of (variation of) parameter in respective periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>sliding velocity $\approx 10^{-4}$ m/s</td>
<td>$s_A$ (incubation distance) = 0</td>
</tr>
<tr>
<td>$v &gt; v_{crit}$ (4 m/s)</td>
<td>$s_A \approx 0-10$ m</td>
</tr>
<tr>
<td>oxygen pressure (increasing: 0 → 1 bar)</td>
<td>$s_A$ tends to smaller value</td>
</tr>
<tr>
<td>surface topography (esp. in ring surface)</td>
<td>$s_A$ is increased by sufficiently deep grooves square to sliding direction</td>
</tr>
<tr>
<td>ring circumference</td>
<td>$f$ related to ring rotation cycle often $s_A = 1$ rev. of ring</td>
</tr>
<tr>
<td>sliding distance $s$</td>
<td>$f$ increases</td>
</tr>
<tr>
<td>load</td>
<td>$s_A$ decreases with increasing load</td>
</tr>
</tbody>
</table>
dominantly built up of ring material. Figures 1.8–11 show the formation of a prow. This process occurs at initially well-fitting surfaces (Fig. 1.8). Subsequent sliding deforms the material in the area of contact, tilting the contact plane and consequently diverging the specimens (Fig. 1.9). Through crack formation at the leading edge of the contact the characteristic prow form arises. With the growth of the prow, from one or both of the running surfaces (Fig. 1.10 and 11), friction increases and a potential wear particle is formed.

Depending on the velocity of sliding \( (v) \) prows may be found on both the running surfaces \( (v < v_{\text{crit}}) \) or only on the ring \( (v > v_{\text{crit}}) \). This transition is connected with the difference in temperature between pin and ring at higher velocity, so that practically a soft pin runs against a hard ring.

During period B1 the running surfaces become progressively more damaged till finally the original topography has vanished completely \( (for v > v_{\text{crit}} \text{ on the ring only partially}) \).

The process of equilibrium B2 is principally the same as B1, but growth of the prows is somewhat smaller and spread over the rough surface of both specimens which are highly work hardened. Often the prows are pressed deeply into the running surface (Fig. 1.13) and to a certain degree overlap like roofing tiles (Fig. 1.7 and 12). The greatest negative pin displacement \( w_{\text{min}} \) in period B1, as well as the bandwidth \( \Delta w \), within which the pin is moving in period B2, clearly depend on the oxygen pressure: the higher the oxygen pressure, the smaller the prows become.

3.1.3. Mild wear C

With sufficient oxygen pressure the severe wear process passes into a process of mild wear. During the transition the coefficient of friction decreases, only to increase to a higher value than in B2. The surface roughness in a process changing from severe to mild is less than in a stable severe process, Fig. 1.4 and 1.5, and gradually diminishes, Fig. 1.6.

3.2. Other metals against a steel ring.

In all cases with other pin materials where metal transfer is involved, independent of the hardness ratio of the sliding partners, the same mechanism of prow formation is found; no principal difference exists between prow formation and rider wear.

4. CONTACT MODEL

4.1. Starting points

Our experimental results correspond very well with those of refs. 5–16. Completion appears possible by working with higher sliding speeds and longer sliding distances, and predominantly by analysing in detail the course of pin position and friction as a function of the distance of sliding. On the basis of the observations a contact model is developed.

Running surfaces touch in a finite number of contact points: generally at least some of these are deformed plastically. In the case of adhesive wear, at least with small and moderate loads, the further development of these contacts is con-
nected with displacement transverse to the running direction of the surfaces (c.f. par. 3 and refs. 5–12). This is wrongly neglected in many existing models.4–18–20.

In every real contact between running surfaces with a translative relative motion, the difference in velocity between the bodies has to be bridged entirely or partially by plastic flow in these bodies (strong and weak junctions). In a wear system as new material is continuously engaged in the process, work hardening should not be neglected. The distribution of the total normal and the tangential load over the contacts depends on the state of the individual junctions. Next we consider the development of a single plastically deformed contact, in which provisionally slip is excluded in the contact surface.

4.2. Flat contact between a plastic and a rigid body

4.2.1. Flow of material during sliding over a short distance

(0) Basic geometry of the contact model. To indicate three principal effects in a simple way, we start from a situation in which the flat surface of a plastic metal 1 is supported by the flat top of a protuberance on a rigid and stationary counter-body 2 (Fig. 2.1.). The contact face is parallel to the nominal motion (velocity v) and is small in relation to the running surfaces; the slope angles $\alpha$ and $\beta$ are small.

(1) Region of deformation above contact face. On sliding without superfacial slip (sticking) the greatest shear stresses lie along the contact face BE in the direction of motion. Without work hardening of metal 1 the difference in speed between the specimens could be bridged by shear in a very thin layer directly above BE (smallest section of junction). Work hardening will increase the specific resistance against further shearing, by which the total shearing resistance of the surface area will outgrow the resistance of a larger zone at a greater distance from the contact face, which is still unaffected by the contact (Fig. 2.2.). Further sliding will lead to shear at some distance above the contact face (Fig. 2.1.). An approach for the determination of the strain and displacement field above the contact plane can be obtained by considering the equilibrium of the ductile metal, that at the time $t = t_1$ is situated between two planes square to the x-axis, with abscissae $x$ and $x + \Delta x$ respectively (not too close to leading and trailing edge of the contact, Fig. 2.3.).

Assuming that shear strains in the sliding direction (parallel to the x-axis) are the only effective strains, then the greatest shear stresses occur parallel to the x-axis (and square to it) while the points where equal maximal shear stresses $\tau(\rho)$ are active, will be situated on cylinder surfaces $\rho$ (not necessarily circular) parallel to the x-axis. These iso-shear stress planes conduct the shear force $\Delta T$, operating in the stationary contact area PQRS, into the ductile metal. Due to the curvature of $\rho$ over the finite contact width, planes at greater distances from the contact area have larger surfaces and equilibrium in the x-direction results in a decrease of $\tau(\rho)$ in planes more remote from the contact.

In the flow region the maximum shear stresses can be correlated to the local shear angle $\gamma$ by applying Nadai’s law for effective stress $\sigma$ and resulting effective strain $\varepsilon$:

$$\bar{\sigma} = c \cdot \bar{\varepsilon}^n,$$

with $c =$ specific stress and $n =$ strain hardening exponent ($0 < n < 1$). As a consequence in planes parallel to the xz-plane a decreasing $\gamma(z)$ is found at higher $z$-values.
Fig. 2. Model for a strong junction between plastic (1) and rigid (2) body.
2.1. longitudinal section of junction, 2.2. transversal section of junction at abscissa x, 2.3. schematic representation of displacements in flow area during a sliding time Δt, 2.4. effect of sliding on strains and displacements during times 2Δt and 3Δt, 2.5. strained area and velocity distributions in longitudinal section of the junction, 2.6. piling-up effect on account of an accumulation in front of the contact face, 2.7. separation of running surfaces by accumulation above the contact face, 2.8. motion of deformation front opposite to sliding direction under the influence of increased load, 2.9. constriction (necking) in the outlet area behind the contact face, 2.10. cracking in constriction area.
The boundary of the shearing region is attained in a plane \( \rho(\delta) \) — intersecting the \( xz \)-plane at \( z = \delta \) — where the plasticity condition \( \overline{\sigma} = \sigma_0 = \sqrt{3 \cdot k} \) is satisfied for the metal supplied to the contact region. This results in a strain and displacement field depicted qualitatively in Fig. 2.3., with \( \gamma(\delta) = 0 \). As the strained region is adjacent to the metal at \( z > \delta \) not influenced by the contact and consequently translating with velocity \( v \), both strain and displacement in the \( x \)-direction of metal in the flow region between \( x \) and \( x + \Delta x \) at time \( t_1 \) increase with time (Fig. 2.4.). Without going into further detail, three important conclusions can be drawn:

(a) As in the direction of sliding the deformation process acts cumulatively while at the leading edge \( B \) of the contact "fresh" metal is supplied into the strained region, subsequent sliding enhances the effective strain \( \varepsilon \) on constant \( z \)-value going from \( B \) to \( E \) (Fig. 2.4.). The correlation of the increase of hardness due to strain hardening has been established experimentally for the differently strained regions above the contact face.

(b) When some sliding distance is available the shear angle \( \gamma(0) \) at the contact plane will increase from \( B \) to \( E \), resulting in an increase in shear stress. The shear force \( \Delta T_c = \tau(0) \). \( \Delta \rhoPRS \) therefore will be greater according as a volume is considered at higher \( x \)-values.

Because of the validity of the plasticity condition at the boundary of the strained region the area of the iso-shear stress plane \( \rho(\delta) \) has to increase in the \( x \)-direction in order to support \( \Delta T_c \); in other words \( \delta = \delta(x) \) and the \( z \)-value of the strained region increases from \( B \) to \( E \). Due to the non-linear character of eqn. (1) the intersections of the deformation front (\( \varepsilon = 0 \)) and of other \( \rho \)-planes with the \( xz \)-plane are curved iso-strain lines (Fig. 2.5.). This conception is supported by experimental evidence.

(c) A consequence of the slope of the deformation front is that under the given velocity limits \( u = 0 \) and \( v \) for \( z = 0 \) respectively, \( \delta \) the velocity profile in the strained region becomes gradually less curved going from \( B \) to \( E \). On the basis of this conclusion it will appear later that the assumption of exclusive shearing in the \( x \)-direction will not hold however, without affecting the conclusions (a)-(c) qualitatively.

(2) Material supply and accumulation. When in a strip \( \triangle ABFJHG \) at the running surface of metal 1 (initial height of strip constant = \( h \)) the local velocity in the \( x \)-direction is \( u \), there could be written for the material conveyance per unit of contact width over \( AG \), \( BH \) and \( EI \):

\[
Q_{AG} = \int_{0_{AG}}^{h} u \cdot dz = v \cdot h \tag{2a}
\]

\[
Q_{BH} = \int_{0_{BH}}^{h} u \cdot dz \tag{2b}
\]

\[
Q_{EI} = \int_{0_{EI}}^{h} u \cdot dz \tag{2c}
\]

Owing to the material resistance above the contact face \( Q_{AG} > Q_{BH} > Q_{EI} \), a material surplus in the strip under consideration exists. Thus accumulation occurs to satisfy the relation of continuity in the area of contact (the geometry allows little lateral flow). This accumulation shows up in \( ABHG \) by piling up of the free
METAL TRANSFER IN SLIDING FRICTION

surface (effect (a) Fig. 2.6.) and in BEIH by separation of the running surfaces with a velocity of \((\text{dw/dt}) = (Q_{BH} - Q_{EI})/BE\) (effect (b), Fig. 2.7). Both phenomena are more effective when the metal work hardens more. Under the influence of (b) the growth of the contact as a consequence of (a) will turn out lower than expected in first instance. The ratio of the effects (a) and (b) depend besides on the work hardening tendency and on the contact length, also on the increase in load at the contact generated by (b). If this is high, then the strain area will move opposite to the direction of sliding, while the contact length rapidly increases (Fig. 2.8.).

(3) Material removal. At some distance beyond the contact face the movement in the strip EFJI is no longer hampered by the contact, so that \(u = v\) holds. This means initially for the material supply per unit of contact width over FJ (Fig. 2.5.):

\[
Q_{FJ} = \int_{0}^{h} u \cdot dz = v \cdot h \tag{2d}
\]

Apparently \(Q_{FJ} > Q_{EI}\), in EFJI a shortage of material arises which shows by constriction of the free surface EF (Fig. 2.9) and possibly by some lateral flow. Continued sliding causes the formation of a groove beyond the contact, the depth of which increases principally until \(Q_{FJ} = Q_{EI}\). The effects derived \(\text{viz.}\) piling up in front of and constriction behind the contact, together with the separation of the running surfaces have been observed experimentally (Fig. 1.9).

4.2.2. Crack initiation

It may be derived that with the described strained area the following deviations from the normal stress distribution around the contact for only normal load are connected:

(a) Extra compressive stresses in the area of piling up in front of the contact.
(b) Increase of hydrostatic pressure above the front part of the contact face (steep iso-shear stress planes and deformation front). Decrease of this pressure above the rear part (flatter deformation front, hence shortage of material compared to the front part).
(c) In the area of constriction—and possibly already at the left side of E in Fig. 2—a three dimensional tensile stress situation of high stress level.

A qualitatively similar stress distribution has been derived for an elastically deformed only contact\(^2\).

The extremely intense shear strains in the region of compressive stresses above the contact face (compare Fig. 1.8–12) generally speaking will not affect the macroscopic coherency of the metal, but in the area of tensile stress they may well do so\(^3\). In the latter area the resistance against plastic deformation according to eqn. (1) has increased considerably by shear strains due to the passing of the contact region, without increase of the cleavage strength of the metal. Under the prevailing three dimensional tensile stress condition it may become energetically more favourable to tear than to satisfy the continuity condition in the area EFJI by plastic deformation (Fig. 2.10). The crack may cut through the crystals, which remained intact under the preceding deformation.

4.3. A contact between two ductile bodies

When running surfaces of the same ductile metal touch, initially a stress
distribution in both bodies may be expected as discussed with regard to the upper body. The normal stresses active on the top and the bottom side of an element of the contact face however, turn out to be different, (Fig. 3.1), and consequently deformations result. As Green derived that the stresses in the vicinity of a side of the junction are lower if its slope is greater \textsuperscript{18}, the deformations may be expected to occur in such a way, that the material supply side becomes steeper and the outlet side flatter (Fig. 3.2.). Thus tilting of the interface opposed to the direction of motion occurs, as confirmed experimentally, (Fig. 1.9 and 10).

With sliding contact between different metals this type of deformation can also be observed (c.f. ref. 24) provided that the weakest partner can strain harden sufficiently during continued sliding. After a short sliding distance the effect has not yet been observed\textsuperscript{13}.

4.4. Contact in an inclined plane

The common surface geometry generally leads to contact in an inclined plane, whereas contacts originally parallel to the sliding motion tend towards tilting. In a junction according to Fig. 4.1, at least the motion of the ductile metal in area ABEHG is influenced by the rigid asperity on the ground of continuity. Without strain hardening the sketched slip-line field with a velocity discontinuity across MLHE and a stationary area BEH may be expected\textsuperscript{18}. Initially the total material supply over AG is carried off over MB (Fig. 4.2). Under the influence of strain hardening however the shearing in plane HE extends to a zone of certain thickness (compare 4.2.1.), say from NO up to K1 (Fig. 4.2. and 3). This implies:

(a) material is being conveyed into the trap BEH, consequently and by the slope of K1 the running surface are separated (c.f. 4.2.1(2)).

(b) the average velocity across EI is lower than the nominal sliding velocity so that, beyond E, a constrictional area with a three dimensional stress emerges (c.f. 4.2.1(3) and 4.2).

Thus with the inclined contact plane again one encounters the effects of the piling up of AB, separation of the running surfaces and constriction in the material outlet area, known from the non-inclined contacts. On account of the sloping position of BE more material will be "trapped" per unit of sliding distance and be deposited in the piled up volume. In the case of a large sloping contact and a long side BC this leads to chip formation.

After a certain sliding distance our model leads to the situation of Fig. 4.4,
Fig. 4. Model for a strong junction between plastic (1) and rigid (2) body on an inclined contact face.  
4.1. situation without strain hardening; slip-line field after ref. 18,  
4.2. material displacements without strain hardening after small sliding distance vΔt,  
4.3. velocity distribution and primary deformation zone in a strain hardening metal 1,  
4.4. piling-up on metal supply side, separation of running surfaces, constriction and possible cracking at the outlet side of the junction,  
4.5. development of junction between two equally plastic bodies.

whereas for a junction of two equally ductile metals the picture of Fig. 4.5 may be expected (compare Fig. 1.9 and 10).

4.5. Development of a junction during longer sliding distance  
4.5.1. Deformation wear  
In the most simple way in which a contact can develop, no crack formation
Fig. 5. Stages in the development of a junction leading to deformation wear.

occurs, even after a long sliding distance. The contact face grows at the material supply side and the deformation front moves opposite to the sliding direction, whereas behind the contact metal is continuously flowing away (Fig. 5.1). Because of the initially increasing distance between the running faces the edge E of the contact might run to the left, by which the net contact growth would be restricted in length and height, but this is not certain (Fig. 5.2). At some time the junction reaches the edge of the test piece (the pin in Fig. 5.3). On account of the permanent cohesion of the specimen to the metal accumulated in the junction, this metal will be left on the donor after the contact is broken (Fig. 5.4). In this way an occasionally intermittent flow of material along the running surface of the donor specimen occurs. When more junctions pass by the edge of the running surface a "beard" of heavily deformed material grows. (Fig. 5.5, c.f. ref. 25).

4.5.2. Metal transfer

Crack formation originating from the constriction area of a junction, leads
to metal transfer in the following way. Due to the growth in height of the junction, the load on it increases causing the contact length at the side of material supply to increase more rapidly than the decrease at the outlet side by the growth of a crack. At the same time the slope of the deformation front rises till an equilibrium value is reached (Fig. 6.1.). The metal which has come to a stand still, readily adopts the prow form observed experimentally (Fig. 6.2.). The net increase in length of the prow front becomes stagnant when the load becomes constant (Fig. 6.3.), either because the junction bears the total test load or because height increase stops on account of increased bending and lateral flow in prow part HGI. The growth of the prow opposite to the direction of motion continues until the edge of the donor is reached and the prow is left on the mating surface as a transferred particle (Fig. 6.4).

Fig. 6. Stages in the development of a junction leading to metal transfer.

and 5). By disturbances the contact may be broken before, at the prow front GH, in the plane of conjunction with the other body or in both places (intermittent prow growth or formation of wear particle).

Between mechanically comparable running surfaces mutual transfer may
occur. Prow generation from materials of the sliding partner means that the biggest prow arises on the smaller of the running surfaces.

### 4.5.3. Energy dissipation

In the deformation areas, on prow formation, a zone around GH in Fig. 6.3 on deformation wear, in a wide area over the contact face, mechanical energy is converted into thermal energy through plastic deformation. With higher sliding speed higher heat flow densities lead to a high local temperature rise, provided the junction is not too small and has an appreciable life time.

### 4.6. Parameters influencing prow formation

The parameters in metal transfer can be related to four aspects of the prow formation process:

1. adhesion and resistance against interfacial slip,
2. process of deformation,
3. crack mechanism,
4. material supply.

For junction development it is necessary that the shear stress in the contact face is sufficiently high to cause tangential shearing of the weaker metal. Of secondary importance is the strength of adhesion (against normal disconnection of the contact) in the tensional stress area. Influencing factors for this aspect are mutual solubility of the metals, surface films, and suppletion of these by physico-chemical interaction from the environment (atmosphere, temperature, contact and regenerating time).

The role of the behaviour under strain is evident and is dependent on the metal lattice, chemical composition of the metal, the phases present and their distribution, rate of deformation and temperature \( (c \) and \( n \) in eqn. (1) decrease on rising temperature). Decreasing wear rate with sliding distance can be related to the continued strain hardening of the surface zones of the test pieces.

The deformation process is also of importance to crack formation because both are competitive in the constriction area, especially behind junctions of greater length. For the crack mechanism therefore the same parameters can be denoted, with resistance against crack propagation or fracture toughness as an important new factor. The greater the energy represented by the crack surface per surface unit of a crack to be generated, the greater the crack resistance (compare fracture mechanics). As the required energy decreases on increasing activity of the atmosphere, the metal will crack sooner and deeper in oxygen than in argon.

This explains the smaller prow size (deformation front GH, material accumulation per unit of sliding distance is smaller Fig. 6.3) as well as the tendency for a shorter incubation period in oxygen.

For continuous development of a junction the supply of material towards the area of deformation has to be sufficiently large. The supply depends on the geometry in front of the contact—slope \( (\beta \) in Fig. 3.1) and height of the asperity on the deforming metal—and on the dynamic behaviour of the sliding system, the need of material depends on deformation depth \( (i.e. \text{on contact length, Fig. 2.5}) \) and the increase of load on growth in height of the junction. When a groove transverse to the sliding direction is deeper than the deformation zone the contact
will be broken. This effect seems to be responsible for prolonging the incubation period when abrading the test pieces transverse to the sliding direction and explains with increasing strain hardening and roughening of the running surfaces, the decrease of the prow size during period B1 (Fig. 1).

5. DISCUSSION

Phenomena in the severe adhesive wear process are obviously:

(a) a junction development, where under the influence of shear resistance in the interface, a field of iso-strain lines (plastic strain) moves through the metal of the wearing surface in a direction opposite to the sliding direction, so that metal accumulates in the junctions and the distance between the running surfaces is enlarged.

(b) cracking of the metal at the backside of the junction, by which material detaches for transfer.

On account of the high contact pressure (adhesion) and the relatively low resistance against tangential shear these phenomena occur especially on contacts already plastic under normal load (c.f. ref. 29). Generally such contacts occur, forming the largest elements in the real area of contact.

Not all the metal accumulated in junctions is transferred, because contact in the interface can cease partially (Fig. 1.10) or entirely (Fig. 1.3) to exist prior to transfer. The probability of transfer in plastic contacts is smaller than 1. Stagnation in growth by interruptions in material supply as well as by break of contact occurs most easily in smaller junctions, with a shallow deformation zone, so that the transferred volume is principally determined by some big junctions. As prows further develop on continued contact, a gradually increasing part of the load is used for this transfer and the wear rate can be reduced by restricting the path of interaction along the wearing surface. Such a system has a lower transfer probability with smaller particles.

The environment has contradictory effects on wear.

A reactive atmosphere reduces prow size by diminishing crack resistance (compare sections 3 and 4.6), whilst for the same reason the transfer probability increases. Therefore a higher wear rate is often found in oxygen than in argon. In order to benefit from the smaller growth of the prows the reactive atmosphere additionally has to reduce the transfer probability through reduction of the slip resistance of the interface (lubricants).

Since prows develop more rapidly on an inclined contact face than on an equally large plane face (section 4.4), it is beneficial to give the hardest surface a smooth finish, at least with flat topped asperities. The difference in hardness of the contacting metals should be such that tilting of the contact face does not occur. Development of prows will also be limited if the strain hardening tendency of the soft partner is small and facilities have been provided in its surface for restriction of the path of interaction. This does not exclude that after a sufficient sliding distance under dry friction heavy wear may occur in such a system by the action of particles generated in repeated transfer on the hard running surface.

The contact model developed, for a qualitative understanding and prediction of the influence of various factors, may also be used as a starting point for
quantifying the influence on wear and friction. For this purpose however, more knowledge of the processes involved and more detail requires to be introduced into the model. Moreover a complete treatise of the severe wear process should include the aspect of removal of the transferred material from the system. Further work on the subject is in progress.

6. CONCLUSIONS

All severe adhesive wear processes can be described on the basis of one contact model, in which plastic deformation and strain hardening, inclination of iso-strain planes, accumulation of material and crack formation in sufficiently strong junctions are central elements.

There appears to be a principal difference between prow formation and deformation wear (whether cracks are formed or not). Gradual differences in prow formation are responsible for the distinction made by Antler et al.\textsuperscript{5–12} in processes of metal transfer.

The new model differs from Bowden and Tabor's concept and from Archard's application of the latter on the calculation of wear rate by emphasizing tear of a junction under an angle with the sliding direction and junction development over a considerably greater sliding distance than the length of a single contact face.

Qualitative, and principally also quantitative predictions of the influence of various factors on the adhesive wear process are possible on the basis of the model.

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