ESTABLISHMENT OF A NEW CLASS OF WEAR: ADHESION INITIATED CATASTROPIC WEAR

D. Markov
Department TM, Railway Research Institute, 3-d Mytishchinskaya st. 10, 129851 Moscow, RUSSIA; e-mail: demit@online.ru

D. Kelly
Department of Engineering, University of Leicester, University Road, Leicester, LE1 7RH, ENGLAND; e-mail: D.A.Kelly@care4free.net

SUMMARY
The nucleation mechanisms and early stages of four types of catastrophic wear (CW), which can be identified as adhesion-initiated (AI) are considered. Close connections are established: a) between two low-energy types of AICW and a disclination mode of plastic deformation and between two high-energy types of AICW and an amorphous mode of plastic deformation, b) between the incidence of either type of low-energy AICW and the hardness of an AICW seed domain relative to that of the friction surfaces, and c) between the onset of AICW and a competitive stripping and reformation of interlayers. Hypothesis on generation and transfer of energy and heat at microlevel (in process of movement of dislocations and disclinations) is developed as a base of amorphous deformation. Attention is drawn to a need for further consideration of terminology in this field.

Keywords: Adhesion; Catastrophic wear; Seizure; Scoring; Scuffing; Galling

1 INTRODUCTION
There are many scientific myths, a number of which have existed from Aristotle's age to the present day - as for example the myth about the stars that can be seen in the afternoon from the bottom of a deep well. Tribology is one of the youngest sciences, but nevertheless (or maybe just in consequence) its myths are among the highest in number. The most widespread of these is the myth, originated in Leonardo da Vinci's work, that there is a certain friction coefficient for each friction pair. Recently, this has been dispelled by the theory of development of intermediate layers (interlayers) in the friction process. Another myth has arisen in pioneering work by the Hardys in the form of an assumption that friction surfaces seize only in stick-slip motion [1]. Subsequently, prominent tribologists have developed theories of plastic deformation, diffusion, melting, collapse of dividing films, and other mechanisms to explain the seizing and tearing of large pieces of material observable in the late stages of wear processes or of clean surfaces at extreme pressure. It has now been established, in numerous research studies, that the transition to catastrophic wear occurs gradually and also that there are different types of unacceptable or catastrophic damage of surfaces in friction. Some elements of the gradual development of individual types of catastrophic wear are mentioned in the theories by A. P. Green, M. Cocks, M. Antler, K. Kato, I. V. Kragelskii and others. G. V. Vinogradov, U. J. Podolskii, and I. V. Kragelskii [2, 3] assumed that there are 2 kinds of seizure - "cold" and "hot"; B. I. Kostetskii [4] picked out two kinds of scuffing – low speed, "low energy" ones and high speed, "high energy" ones; V. I. Kashcheev [5] distinguished between cold scoring, in which hardness plays a governing role, and hot scoring, in which wear rate depends to some extent on initial hardness.

2 TYPES OF CATASTROPIC WEAR AND THEIR FEATURES
The initial stages of catastrophic wear have been investigated by the present authors [6] and it has been shown that, for steel/steel friction pairs, at least four types of catastrophic wear take place, two of which may be described as low-energy types, and two as high energy types. All four begin gradually with adhesive interaction of micro-asperities; this gives a reason to identify a new class of wear - Adhesion Initiated Catastrophic Wear (AICW). To the four types of AICW we have assigned terms already in use. We have tried to minimise the inevitable conflicts with the older, less precise, usage. Perhaps the committees working on the development of the terminology of the subject will be able to find more acceptable terms. The AICW types and the conditions for their occurrence are summarised in Table 1:

<table>
<thead>
<tr>
<th>Types of Adhesion Initiated Catastrophic Wear</th>
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<tbody>
<tr>
<td>Low Energy</td>
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<tr>
<td>Seizure</td>
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<tr>
<td>Criteria for incidence in medium carbon steels</td>
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<tr>
<td>Sliding Speed $&lt; 0.4 - 0.7$ m/s</td>
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<tr>
<td>$H_{\text{edge}} &lt; H_{\text{surface}}$</td>
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* $H$ is hardness; $T$ is temperature

Table 1: Classification of AICW and criteria for their incidence.

The environment is not critical for the incidence of any AICW type: all AICW types can occur in all media depending on local pressure and sliding speed at least in principle.

2.1 Types of deformation and types of wear
One of the basic ideas of the classification put forward is correlation of wear mechanisms to deformation...
mechanisms that have some generality, at least for medium carbon steels. For some time now, almost all friction phenomena have been examined from the position of the theory of dislocations. More recently, following V. I. Vladimirov [7] and V. V. Ribin [8], even for comparatively small deformation prior to rupture of metals, the dislocation mechanism has been replaced by the disclination concept, based on the rotation of larger structural elements. Transition from the dislocation to the disclination mechanism is accompanied by a change in the work-hardening coefficient of body-centred cubic metals. The dependence of hardness on shear strain within surface layers of 0.6% C steel rollers is shown in Figure 1. The dislocation mechanism predominates in a range of deformation from 0 up to ~100 %, typical for mild wear.

Figure 1: Dependence of hardness on shear strain in surface layer of steel rollers: 1 – 0.53%C; 2 – 0.65%C. Rolling-sliding friction was used to form the structure of surface layer

In catastrophic wear the intensity of deformation approaches infinity and the dislocation mode of deformation should be replaced by another mode. At sliding speeds less than 0.4 - 0.7 m/s this is a disclination mode (low energy type of AICW). At sliding speeds more than 0.4 - 0.7 m/s it is an amorphous mode (high-energy AICW). We introduce the amorphous mode of deformation of polycrystalline metals to explain the rather abrupt changes in properties and appearance of surface damage observed on transition from low to high sliding speed.

2.2 Low energy types of AICW

In AICW at low sliding speed, whether seizure or scoring occurs is conditioned by the hardness of the friction surfaces relative to the hardness of an adhesive centre or seed domain formed by interacting asperities. Scoring. If the hardness of the AICW seed exceeds the hardness of both friction surfaces, then wear develops by the scoring mechanism. Four stages of scoring development are shown schematically in Figure 2. It has been shown by J. A. Greenwood and D. Tabor on models [9] and N. M. Alekseev on samples [10], that if the surfaces are close in hardness, then material flows circularly around the local adhesive connection and as a result the connected zone contracts to a hardened point. This point is the seed curl of scoring, Figure 2c. At later stages the seed curl stops rotating and begins to slide over one of surfaces. This results in formation of a wedge at first on one surface, and then on the other. A cross-section of one such wedge is presented in Figure 3. The wedges slide by turns. Sliding and fixed-bed wedges have different shapes. They interact mechanically and easily separate from each other when the surfaces are disturbed (e.g. for metallography).

Figure 2: Scoring: development of curl and wedges. a - initial contact, b - deformation of asperities with rotation of interface, c - seed curl (or rider) formation, d - wedges formation

Figure 3: Cross-section of wedge at surface of medium-carbon steel roller

Seizure. If the hardness of the adhesive seed does not exceed the hardness of either friction surface then wear develops by the seizure mechanism. Figure 4 shows, schematically, a hard asperity sliding over a soft one. Seizure develops by transfer and local accumulation of portions of soft metal on longitudinal hard ridges; this results in increasing pressure on them, their lateral integration and the gradual formation of a hardening prow. Strong adhesion of transferring metal to a rigid asperity requires a friction force in excess of the shear strength of rapidly hardening material. In scoring the generation of a seed curl requires tangential forces only slightly in excess of the yield strength of unhardened material. Therefore the critical pressure for seizure is much more than that for scoring.
A basic factor that inhibits the development of catastrophic wear, even at the high pressure, is the presence of separation films (oxide, adsorbed, and other). Irrespective of their nature, such films on a hard asperity are stripped during its interaction with opposing asperities and are restored during its passage over valleys. Surface films and surface layers of friction bodies form interlayers (originally referred to as a “third body”), in which shear and friction force are originated and concentrated. Interlayers develop and change continuously during rubbing; friction coefficient, therefore, can not be a constant attribute of a given friction pair. The expected variation in local friction coefficient on microasperities is shown in Figure 5 schematically.

The deformation should not exceed ten percent or so, and will be approximately equal in the longitudinal and lateral directions while the friction coefficient is low. A comparable situation may be observed in the rut left by a ball sliding across a plate. The longitudinal elongation of the surface layer in the centre of the rut (width of rut is approximately equal 1/3 radiuses of the ball, steel/steel pair, $f = 0.145$) is found to be of the order of 10%.

In both seizure and scoring, dynamic stripping and restoration of separation films become manifest at both micro-level, and macro-level. At microlevel – as a dependence of critical pressure on sliding speed that arises because the greater the sliding speed, the shorter the intervals of time for restoration. At macrolevel – as an asymmetry in the influence of relative hardness on transfer in pin-on-disc tests that arises because on the pin there are, again, shorter intervals of time for restoration. This sensitive balance between stripping and restoration can be expected to play a role in the onset of all types of AICW.

2.3 High energy types of AICW

**Galling.** Traditional theories of what happens are based on the hypothesis that the influence of temperature on wear type acts, in essence, through a thermal change in the mechanical properties of the affected surface layer material. This results in a sharp increase of adhesion force and transfer of material. However, chronologically, plastic deformation (or flow) of material occurs before energy is transformed into heat. The question what is primary, heating or deformation, passes from a philosophical to a practical plane if it is assumed that, at high speeds, deformation and transfer of metal occur without essential heating. In [2] it was shown that, for speeds above 0.4 - 0.7 m/s and shock loading, the transferred metal has very high hardness – up to 1400 HV$_0$. In [11] and [12] the reported microhardness of thin layers of a 0.45%C steel, transferred in high-speed scuffing, reached 1900 HV$_0$. In [2], to explain so high a hardness, the hypothesis was put forward that at sliding speeds above 0.7 m/s dislocation or disclination mechanisms do not work and metal flows amorphously. During amorphous flow in a thin surface layer the atoms of carbon, nonmetallic inclusions and other defects chaotically mix with atoms of iron, forming an extreme stressed structure – a metal glass – and acquire energy proportional to the speed of deformation. The interacting micro asperities are smeared amorphously over the friction surfaces. This transferred metal forms protrusions which increase in size with repeated interactions, Figure 6, top left corner.

The mechanism of heating of metal during plastic deformation can be visualised as follows. As atoms move on the shear plane (in the gliding line of a dislocation or the rotating surface of a disclination) their energy rises periodically to a high level and falls back to a low level synchronously with the period of the crystal matrix d, Figure 7.
Waves generated by their motion can be treated as phonons. Matrix of crystal bodies is characterised by a maximal frequency of normal oscillations $\omega_{\text{max}} = v (6\pi^2 n)^{1/3}$, a minimal wave length $\lambda_{\text{min}} = (2\pi\nu)\omega_{\text{max}} = 2/(n)^{1/3}$ and a Debye characteristic temperature $\theta_D = h \omega_{\text{max}} / k$ [13], where $d$ is the lattice spacing (period of the crystal matrix), $\hbar$ is Planck’s constant, $k$ is Boltzmann’s constant, $n$ is the number of atoms per unit volume ($3n=\omega_{\text{max}}1/3(2\pi2ez3)$ is the number of degrees of freedom), $\nu$ is the phase velocity of the wave in the crystal and $\epsilon$ is the speed of movement of the dislocation or disclination. The frequency of the phonons is defined by the speed of movement of the dislocations or disclinations: $\omega = \epsilon / 2d$. Phonons are acoustic (mobile) if $\epsilon$ is low and thermal (stationary) if $\epsilon$ is high. The energy of each phonon is $E_p = h \omega$ , so that its temperature, in the gliding plane, is $T_p = h \omega / k$. The effective temperature of an isolated slide band can be derived from the sum of the phonon energies in unit volume of slide band:

$$3n_{up} = U_0 + \frac{9n \hbar}{\omega_{\text{max}}^3} \int_0^{\omega_{\text{max}}} \frac{\omega^3 d\omega}{e^{\hbar\omega/kT} - 1}.$$ 

The energy of acoustic phonons transfers by phonon-phonon interaction. The energy of thermal phonons is transmitted by the electron ‘gas’ at medium to high deformation rate and by photon-electron interaction at high deformation rate (by heat radiation). As the speed of deformation increases, the frequency of the atoms’ relocation, heat radiation and the resistance to movement of dislocations or disclinations grow. It is argued that there is a rate of deformation at which neither dislocations nor disclinations can move and deformation is realized by means of high-speed amorphous flow of atoms in a slide band. When $T_p \approx T_{\text{melting}}$ a majority of atoms have no time to fall back to the low level and stay at a high energy level, $u_p = h \omega_{\text{max}}$. It is for this reason that the phrase “high energy AICW” is adopted.

As distinct from the dislocation and disclination modes of deformation, amorphous deformation produces an increase of hardness - not during the process - but after flow cessation only. As a result, the layers of the deformed metal are thin and homogeneous, and the grooves are shallow and extend slowly. In places having good contact with bulk metal the smeread metal returns energy rapidly and has little time to heat after leaving the friction zone. It retains the amorphous structure (of a "metal glass") and has the highest hardness. If the adjacent heatsink is poor then little energy can flow from the transferred metal; its temperature rises and its hardness falls. This is confirmed by the observation of regions of transferred metal of very high hardness (~1400 HV_{0.1}) having good thermal contact with the bulk metal and regions of moderate hardness (~800 HV_{0.1}) having poor thermal contact, Figure 8. Judging from observed oxide tints, the temperature at the ends of galling plates where metals of disc and pin intermixed and the heatsinks were good was less than 100 °C; the temperature at the beginnings of galling plates where the heatsinks were bad was about 300 to 400 °C, (see Figure 6). If the sliding speed is lower than ~0.7 m/s galling is replaced by a low energy type of AICW, scoring or seizure, with deep extending grooves, which can be seen in the bottom right corner of Figure 6.

**Scuffing**. Details of the scuffing process are obscured by its very short time of evolution. Only the initial and final stages of its development are readily observed. But what can be said with confidence is that the loading rate is rather slower than in galling and a significant rise in temperature of the oil film (and perhaps the metal) precedes its onset.

**3 CONCLUSIONS**

Thus, it is possible to allocate four types of catastrophic wear, all of which are adhesion-initiated; two of which may be termed ‘low-energy’ types and two ‘high-energy’. All four are characterised by a concentration of...
normal load and localisation of plastic flow on one or both surfaces of a friction pair within a small area (the adhesive centre of AICW) resulting in the rapid formation of large protrusions and widening grooves on the surfaces and in sharp increases of surface roughness and wear rate. It is emphasized that each type of AICW is identified in terms of the initial stage of its origin since, firstly, the initial stage helps define means of their prevention, and secondly, at later stages one type can change to another and introduce difficulties in understanding. For the purpose of designation of the AICW types, four names have been given a more specific usage in the present paper than has previously been the case. Refined definitions of these terms, in accord with this usage, are now put forward:

**Seizure** is characterised by plastic deformation of one surface only, by macroscopic adhesive transfer of material from a softer surface onto a harder surface and by formation of widening grooves on the softer surface and protrusions on the harder surface.

**Scoring** is characterised by plastic deformation of both surfaces, by absence of macroscopic adhesive transfer of material and by formation of self-organized centres of scoring – curls – which at a later development stage are replaced by pairs of mechanically interlocked wedges alternately developing on and sliding along the friction surfaces from which they are generated.

**Galling** is characterised by adhesive transfer of micro volumes of material from a softer surface onto a harder surface with subsequent amorphous deformation of material of both surfaces and smearing of mixed material on the surface having shorter time intervals for separation film regeneration.

**Scuffing** is characterised by friction heating and softening of material of one surface and transfer of it onto the other, cooler surface.

It important to note that catastrophic wear is not restricted to initiation by adhesive interaction only; it can arise by abrasive interaction also. Particles of some soft, but fast hardening materials tend to become impressed into the deeper microrelief on hard surfaces and to be strongly held there (for example, copper in scratches on a steel shaft [2]). Such transfer, after merging of the separate centres can be indistinguishable from adhesion-initiated transfer. It is also possible, that abrasive particles can play a role of seed curl and cause scoring. These types of wear should be classified as abrasion-initiated. The classical model of such processes is the choking of a file by annealed aluminium or copper. It is necessary to distinguish adhesion- from abrasion-initiated processes, as the reasons for their occurrence and the methods for their elimination differ. For example, the abrasion-initiated transfer of copper onto a steel shaft decreases as the roughness of the shaft decreases and as ingress of abrasive particles is prevented. In contrast, adhesive wear can increase as the roughness of the friction surfaces decreases.

Currently, in all countries, terminology of greater precision is developing in the field of catastrophic wear. The names given here, to four types of AICW classified in terms of originating mechanisms, are put forward with some diffidence because they have little etymological connection with the corresponding mechanisms. There is a need for international councils of tribologists to give further consideration to identifying appropriate terminology.

### 4 REFERENCES


