ABSTRACT
Dry sliding wear tests were performed using a ring-on-block configuration for copper sliding against steel. The wear mechanisms of this pair were investigated under different load ranges and sliding velocities. During the tests, the bulk temperature in the near-surface contact region was continuously recorded.

The results of scanning electron microscope (SEM), energy dispersive X-ray spectrometry (EDS) and nanoindentation tests on the worn surfaces and the debris reveal a commanding role of the steel in the wear mechanisms of the pair. Additional tests of steel-steel pairs corroborate this assumption. It will be shown that the different wear mechanisms, which the steel experiences over the test range, markedly influence copper wear rates. Metallographic investigations on cross sections of copper samples show the formation of recrystallized layers on the worn surface at high sliding speeds. The onset of recrystallization is accompanied by extrusion of wear debris.

1. INTRODUCTION
The combination of copper and steel as a tribological pair is widely used in many industrial applications, especially of the electro industry. Electrolytic Tough Pitch copper is the most widely-used copper for electronic products based on its optimum combination of workability, performance, and economy. Most of the time friction takes place under dry conditions.

The aim of this paper is to investigate the fundamental wear mechanisms in dry sliding friction tests of copper versus steel. During the tests under different sliding velocities and loadings the bulk temperature in the near-surface contact region of copper specimens and the acting friction forces on the interface between the copper and steel, were continuously recorded.

2. EXPERIMENTAL
The materials under investigation were: electrolytic tough pitch (ETP) copper (99.9 wt. %Cu) and hardened SAE 4620 steel. The mechanical properties of the samples are: hardness under load, measured in recording hardness tests 1.1 GPa for Cu and 7.8 GPa for steel whereas the elastic modulus for ETP copper 117 GPa and 210 GPa for steel. The copper were supplied in an as-cast condition from which wear samples (rectangular blocks of 5x10x15 mm) were machined. All steel samples were bought prepared similar to the copper blocks. The counterpart in all wear tests were SAE 4620 steel rings with an outer diameter of 40 mm.

Sliding wear tests were performed on a ring-on block wear machine within a load range of 3-310 N and a sliding velocity range of 0.2 – 2.0 m.s⁻¹. All samples (block and ring) were ultrasonic cleaned in acetone and weighted before the test. From the difference in their mass before and after the test the mass wear rates were calculated. For this the mass difference were divided by the sliding distance.

The near surface bulk temperature Tₙ of the copper block specimen was measured with the help of a commercially available thermocouple (constantan/Cu) probe, which tip was located approximately 2μm from the contact surface. The probe was inserted through a hole drilled at an inclined angle through to the sliding surface and the temperature was continuously recorded. The end of the probe was initially in contact with the steel ring but with proceeding of the test the hole was covered by wear debris. To characterise the composition and morphology of the worn surfaces as well as the debris, scanning electron microscopy and energy dispersive X-ray spectrometry was used.

After that sub-surface metallographic cross-sections of the block specimen were made. To reveal the microstructure at the worn surface these cross-sections were then etched with a solution of H₂O, HCl and FeCl₃.

3. RESULTS
The wear behaviour of the Cu-Sample and the steel-ring versus the applied normal load F at the various sliding speeds are plotted in Fig.1 and Fig.2, respectively. The range of speeds and loads used for wear tests extended over both mild and severe wear rate regimes. The tests
carried out in all wear regimes reached well into steady state conditions where the test duration was generally greater than 2 hours. The criterion for steady state was here the attainment of constant bulk temperature. In the severe wear regime even for high loadings and sliding speeds no onset of seizure could be recorded. However, for loads $F > 40 \text{ N}$ at a sliding speed of 2 m/s extensive plastic deformation of the Cu-specimen was seen but never, as it is typical for seizure, a material transfer to the adjacent steel counterface.

Whereas the transition from mild to severe wear for the Cu-specimen is continuous the steel shows a rather discontinuous behaviour (Fig.2).

Figure 1. Wear Rate versus applied load at different sliding velocities for ETP copper against steel in a Ring-on Block configuration

Figure 2. Wear Rate versus applied load at different sliding velocities for SEA steel in a Ring-on Block configuration with ETP copper.

The steel undergoes different wear mechanisms, where it experiences a transition from mild to severe to mild wear. Additionally tests on steel-steel pairs, shown in Fig.3 observed a change from mild to severe wear depending on the load and sliding speed. There is also a possible transition from mild-severe-mild wear, as it might be the case for the test at 1m.s$^{-1}$.

3) As proposed by [3], the wear and friction characteristic are determined by the properties of the built up layer. During the tests the mechanisms can change from adhesion (high C.O.F) to 3 body abrasion stages (lower C.O.F) depending on the chemical composition of the layer on the contact surface.

4) Additional tests on SAE steel-steel pairs show a possible correlation to the assumed wear rate mechanisms change for steel on steel as found in [2] for the used load ranges.

4. SUMMARY

In conclusion the changes in wear mechanisms of the steel at 10-50 N range results in:

1) Increase in Cu wear at $T_b$ of 40°C (0.2m.s$^{-1}$) and 85°C(1m.s$^{-1}$), respectively. For the test at 2m.s$^{-1}$ no such drastic change in the wear rate of the copper was recorded. A possible explanation is the already high bulk temperature $T_b$ for low loads, which changes the wear mechanisms. A proportional relationship between wear rate $W$, load $F$ and sliding velocity $v$ as it was found by [1] could not be detected.

2) The steel undergoes different wear mechanisms, resulting in a sudden increase in wear. Tests on steel-steel pairs[2] and Figure 3 observed a change from mild to severe wear depending on the load and sliding speed. There is also a possible transition from mild-severe-mild wear, as it might be the case for the test at 1m.s$^{-1}$.

3) As proposed by [3], the wear and friction characteristic are determined by the properties of the built up layer. During the tests the mechanisms can change from adhesion (high C.O.F) to 3 body abrasion stages (lower C.O.F) depending on the chemical composition of the layer on the contact surface.

4) Additional tests on SAE steel-steel pairs show a possible correlation to the assumed wear rate mechanisms change for steel on steel as found in [2] for the used load ranges.


Sincere thanks to H.Hawthorne and S.Wilson for support and discussions. Part of this work was supported by a scholarship of the Deutsche Akademie der Naturforscher - Leopoldina.