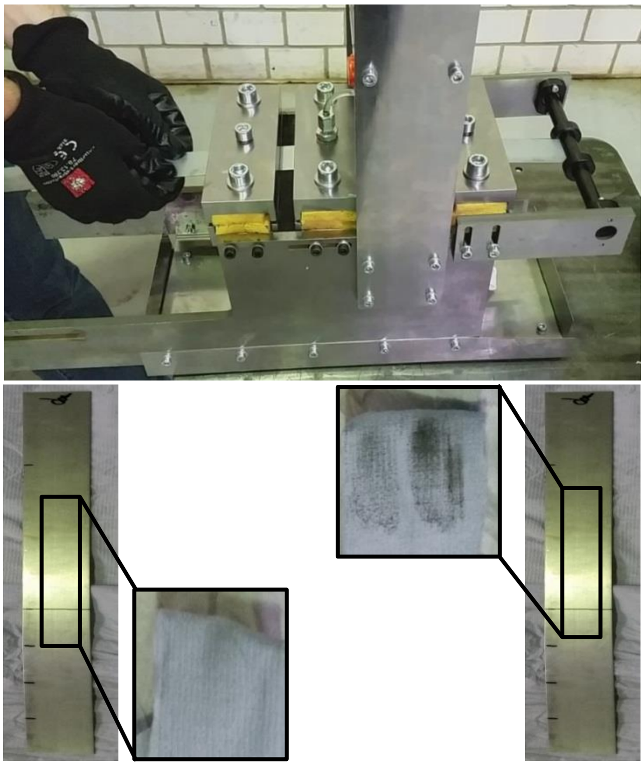

Fig. 3: Cleaning station without air nozzles (upper picture); wipe test before cleaning (bottom right picture); wipe test after cleaning (bottom left picture)

The wipe test, depicted in Fig. 3, shows the presence of significant macroscopic contamination of the sheet metal before cleaning. This can be attributed to the prelube oils which are used in commercial sheet metal production for corrosion protection. The wipe test in the left bottom picture shows a macroscopically clean sheet metal surface after passing the cleaning station within the first three cleaning steps. During the investigations the fresh material was continuously cleaned in the cleaning station. The cleanliness of the sheet metal surface was regularly manually checked with wipe tests. In case of detectable contaminations, the sponges of the station were cleaned or if necessary renewed.

In the present study two specimens with α-Fe_2O_3 layer were tested. Table 1 shows the parameters of the wear tests. The specimens A1 and A2 were tested with equal surface pressures and process temperatures. While specimen A1 was tested up to 100 strokes (6 m) specimen A2 was loaded with 5000 strokes (300 m). The sliding speed in both cases was 40 mm/s.

Tab. 1: Test parameters of wear investigations.

Specimen	**Strokes** [-]	**Path per stroke** [mm]	**Surface Pressure $\bar{p}$** [N/mm²]	**Temperature** [°C]
A1	100	60	80	80 ± 5
A2	5000	60	80	80 ± 5

3 Results

Before and after the experiments on the test bench macroscopic and microscopic analyses were carried out. For this purpose the specimens were marked on the front face at three angles over the contact area which equals one quarter circle of the cylinder. These are the inlet area (0° angle), the central area (45° angle) and the outlet area of the sheet metal (90° angle). The inlet area showed the most distinctive layer wear, which was attributed to the bending of the sheet metal in this area. By contrast the outlet area had the lowest layer wear, and was partly uneven. Therefore the central area at an angle of 45° to the drawing direction was chosen as the area best suited for the analyses. Here, a uniform layer wear over the whole contact area between the sheet metal and the specimen's surface took place. All following data refer to this area. The observation of the specimen started with macroscopic screening followed by digital light microscopy and scanning electron microscopy (SEM). The light microscopy images were carried out using a digital light microscope (Keyence VHX-1000). For high resolution scanning an electron microscope (SEM), Zeiss Supra 55 VP, equipped with an energy dispersive X-ray spectroscopy (EDX) detector was employed. A secondary electron detector and a low acceleration voltage of 7 kV were used to achieve high resolution without significant charging effects of the oxide covered surfaces.

In Fig. 4 an untested specimen is shown at three magnifications. The top image in Fig. 4 shows an oxidised specimen with α-Fe_2O_3 layer prior to testing. The whole surface of the specimen has a red/blue discolouration as a visible result of the surface oxidisation [1]. A higher magnification with a light microscope (middle picture in Fig. 4) reveals that not all of the surface is covered with the oxide layer. The highest magnification in Fig. 4 (bottom image) reveals the microstructure of the oxide layer. The α-Fe_2O_3 layer looks like an arrangement of long polymer chains. The layer is covering the largest part of the section shown, but there are also other uncoated areas.

The coverage of the surface with α-Fe_2O_3 strongly depends on the local composition of the substrate. The investigated hardened tool steel (1.2379) has a high chromium content of approx. 12 wt.-% and chromium rich precipitations with different sizes could be detected by SEM-EDX. Surface areas that featured precipitations were usually not covered by the α-Fe_2O_3 unless these were very small. Thus, it can be reasoned that the metallic sparkling areas in the top image of Fig. 4 are uncoated chromium rich areas.

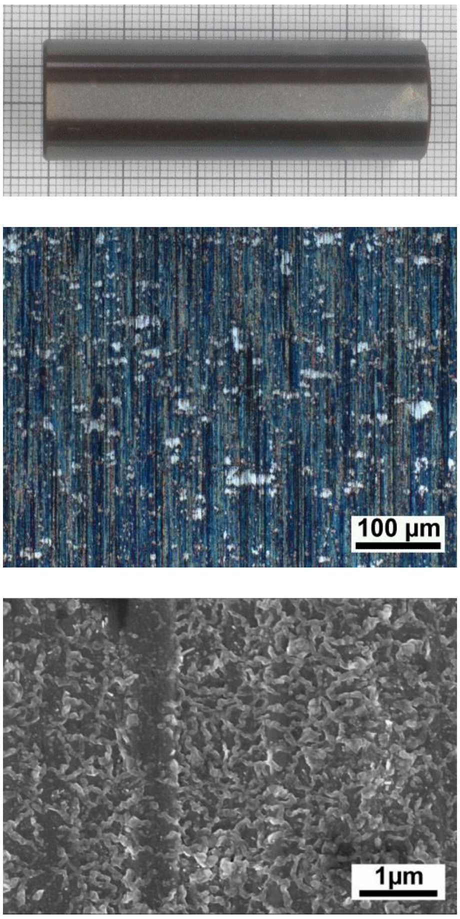

Fig. 4: Selectively oxidised α-Fe_2O_3 specimen. Top: photo of untested specimen; mid position: digital light microscopic image; bottom: SEM image

Depending on the number of test cycles the surface of the specimens changed after the wear tests. In Fig. 5 the tested specimen A1 is shown after 100 strokes. The photo (top picture) in Fig. 5 presents the macroscopic appearance of the specimen after testing. While in the bending area of the sheet metal (0° angle) a layer thinning can be seen, the evaluated area (45° angle) shows no significant changes on the surface on the macroscopic scale. In addition, slight marks on the left and right side in the contact area with the sheet metal can be seen in the photo in Fig. 5. These are results of the sheet metal burr cutting into the surface. This phenomenon is increasing with the number of strokes but not relevant in the present context because in commercial deep drawing operations such contact conditions are not present.

The light microscopic image of specimen A1 (middle image Fig. 5) only shows slight changes as compared to the light microscopic image of the untested specimen (Fig. 4). Only a few additional scratches along the sliding direction (vertical in the image) can be seen. Furthermore metallic sparkling areas are now visible and it seems that the size of these areas has also increased. It can be assumed that their higher fraction is a result of a partial removal of the α-Fe_2O_3 structure. The α-Fe_2O_3 also covered the edges of chromium rich precipitations. This leads to the conclusion that the increased fraction of the oxide-free areas can be reasoned by the reduced bonding of the oxide to the substrate at these chromium rich areas. In the SEM image in Fig. 5 (bottom picture) the surface appears very different, as compared to the SEM image of the untested specimen (Fig. 4). The structure of the oxide layer seems to be smoothed and rounded but is still visible.

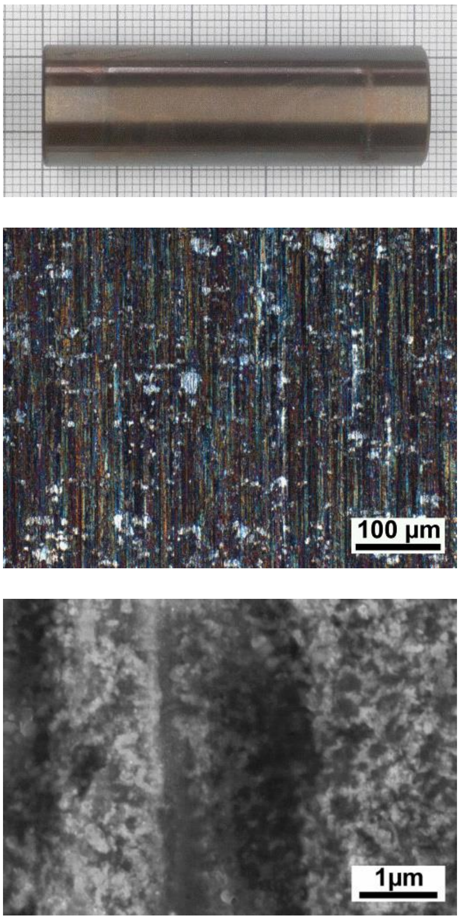

Fig. 5: Selectively oxidised α-Fe_2O_3 specimen after 100 strokes; top: photo of tested specimen; mid position: digital light microscopic image; bottom: SEM image

After a substantial increase of the number of strokes to 5000 a thinning of the α-Fe_2O_3 layer can be seen clearly at each magnification (Fig. 6). The photo in Fig. 6 (top) reveals that the layer has become thinner over the whole contact area. But even after 5000 strokes a remaining layer can be seen clearly also in light microscopic image (middle). In addition to the layer thinning the middle image shows scoring in the drawing direction. Also zinc pick-up from the hot dip galvanized sheet metal used was detected by EDX. The SEM image in Fig. 6 (bottom) clearly shows features that are an evidence for the existence of α-Fe_2O_3 on the surface.

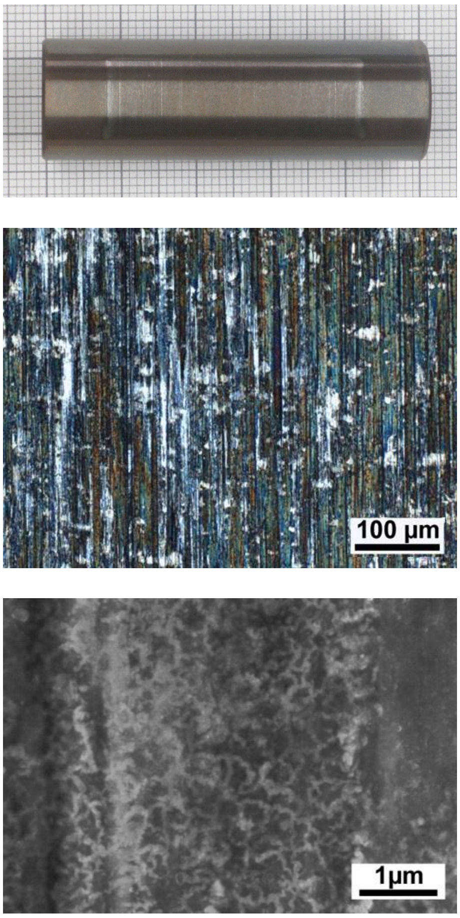

Fig. 6: Selectively oxidised α-Fe_2O_3 specimen after 5000 strokes; top: photo of tested specimen; mid position: digital light microscopic image; bottom: SEM image

4 Summary and Outlook

Within the present study wear experiments on specimens with selectively oxidised α-Fe_2O_3 layers were conducted with a surface pressure of 80 MPa at a process temperature of 80 ± 5 °C. The results can be summarized as follows:

It was shown that the generation of the oxide layer depends on the local composition of the surface. Surface near chromium rich precipitations were usually not covered by α-Fe_2O_3, and thus, a complete coverage of the specimens was not realised.

Even after 5000 strokes of load (300 m of sheet metal) the friction reducing α-Fe_2O_3 was still present on the surface, which indicates the potential of these coatings for demanding applications in dry metal forming.

Small amounts of zinc were detected on the oxidised specimen that was tested up to 5000 strokes. Whether the transfer of zinc adds to the durability of the coatings is, however, not clear yet.

It appears that oxidised surfaces might be a viable approach to realise dry metal forming as the oxides provide for low friction coefficient and feature substantial durability. Clearly, further studies need to address the tolerable maximum surface pressure between the sheet metal and specimen and how pressure affects the wear behaviour over extended periods of usage.

Acknowledgements

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