Tab. 1: Si-contents and properties of the tested a-C:H coatings

| Coating | Si-Content [Atm.-%] | Thickness [µm] | Hardness [GPa] | Ra ball-on-disc [µm] | Ra strip drawing [µm] | Abrasive wear [$10^{-15}m^3/Nm$] |
|---|---|---|---|---|---|---|
| Si 0% | 0 | 2.2 | 34.1 | 0.055 | 0.050 | 1.0 |
| Si 8% | 8 | 2.7 | 20.2 | 0.088 | 0.034 | 1.4 |
| Si 16% | 16 | 2.3 | 17.0 | 0.070 | 0.049 | 6.1 |
| Si 25% | 25.3 | 2.8 | 18.6 | 0.079 | 0.050 | 10.1 |
| Si 34% | 33.8 | 2.7 | 19.6 | 0.053 | 0.078 | 16.42 |

Tab. 2: Test parameters of the ball-on-disc tribometer and strip drawing test

| Test | Load [N] | Initial contact stress [MPa] | Sliding speed [$mms^{-1}$] | Sliding distance [m] | Humidity [%] | Temperature [°C] |
|---|---|---|---|---|---|---|
| Ball-on-disc Tribometer | 1 | 300 | 50 | 180 | 40-60 | 24.5 |
| Strip-drawing | 9000 | ~ 75 | 100 | 0,1 | - | 26.0 |

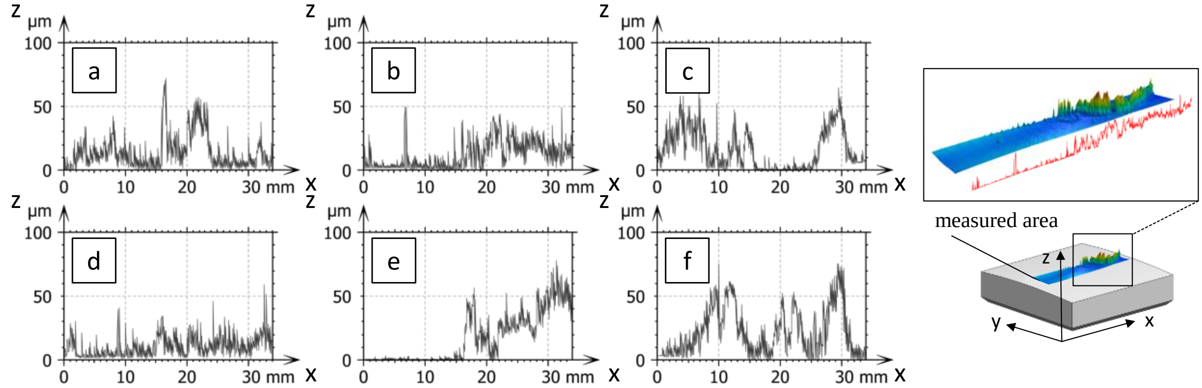


Fig. 3: Adhesions characterized by envelopes of a profile series for each tool configuration

times to improve the statistical quality of the friction and wear values. The test parameters were deduced from an industrial forming process of EN AW 5083 aluminum and are summarized in table 2. Higher contact stresses in the ball-on-disc tribometer tests were used in order to accelerate wear, whereas the strip drawing test is more oriented towards a realistic load spectrum in sheet metal forming.

After performing the tribometer tests, the wear amount on the aluminum sheets was determined by a tactile measurement method (DektakXT - Bruker). Therefore, a nano indenter measured the topography across the wear track. In the topography, the area above the zero line denotes material adhesion and the area under the zero line denotes material removal. The tactile measurements were performed at five different points along the wear track to gain an average wear value.

The tested balls were analyzed with a light microscope to determine the wear amount indicated by the diameter of the wear track. Additional analyses with a raster electron microscope (REM) and an energy dispersive x-ray spectroscope (EDX) allowed an identification of aluminum adhesions on the wear track.

## 3 Results and discussion

### 3.1 Strip drawing test

In general, all tested coatings show severe adhesive wear on the tool surfaces after the first 100 mm stroke under the applied load of approximately 75 MPa contact normal pressure.

The results in Fig. 3 show the macroscopic adhesions on the tool surface after the first stroke. For all tool surfaces, a section of 34 mm by 5 mm (x by y) is digitalized by confocal white light microscopy. All profiles are extracted for each measurement and their envelope represents the maximum height of adhesions in this area.

The test results do not allow a prediction about differing adhesiveness of the different coating configurations. In all cases the adhesions after the first stroke are already macroscopic and do not show any systematics regarding Si-contents. Due to the instant formation of adhesions and the early strip failure it is not possible to investigate the underlying mechanisms for which reason the following ball-on-disc tests were performed.

### 3.2 Ball-on-disc test

Fig. 4 shows the average friction values of the tested coatings after the run-in period. The friction values increase up to 16% and between 25% and 34% linear with an increasing content of silicon. Between 16% and 25% the value remains constant. This anomaly may be a result of superposing wear mechanisms and will be discussed later in this study. The increasing friction values validate the friction behavior of a-C:H:Si coatings sliding against aluminum A1100 reported by Murakawa [12] for the sliding contact against aluminum EN AW 5083.

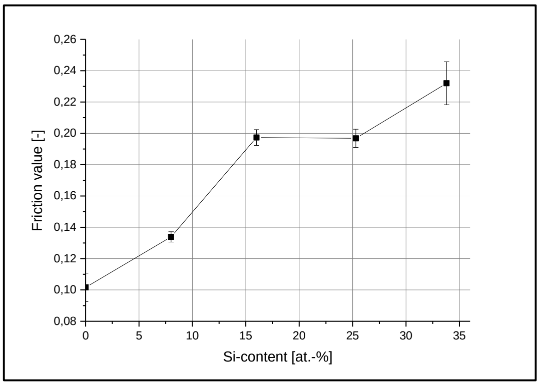


Fig. 4: Average friction value of the tested coatings after the run-in period

It is noticeable that every coating (Fig. 5a-e) showed an individual tribological behavior. At the beginning of the tribometer tests, the friction coefficients assume high values, ranging between μ = 0.78 (Si0%) and 1.16 (Si34%) dropping to a lower level after a certain period of time and remaining steady. The high friction level is known as run-in period and varied depending on the tested coatings. With an increasing content of silicon in the a-C:H matrix, the duration extended from tri = 90 s for Si0% to 2600 s. for Si34%.

The tests with uncoated steel balls (Fig. 5f) show a different tribological behavior. The run-in period lasted 1000 s and the friction value remained at a high level with an average value of μ = 0.51. This high friction level is typical for a dry sliding contact against aluminum and was caused by a constant formation and disintegration of aluminum adhesions on the ball surface [1], see fig. 6f.

The friction level during the run-in period of the Si25% and Si34% coatings equals the friction level of the uncoated balls. Thus a formation of aluminum adhesion on the coated surface is a possible explanation for the higher friction value. But in comparison to the uncoated ball, no aluminum adhesions were formed directly on the wear track of the coated balls, see fig. 6a-e. Due to the abrasive wear, one of the tested Si34% coatings was completely removed at the end of the tribometer test, see fig. 7. In consequence, aluminum adhesions were formed on the exposed steel surface and the friction value increased at the end of the test (fig. 5e). Both the non-adhesive wear tracks in fig. 6a-e and the formation of aluminum adhesions after a complete removal of the coating prove the low adhesion tendency of the tested coatings.

In comparison to the tribometer tests against steel reported by Oguri [8], the incorporation of silicon leads to a linear increasing friction value in contact with aluminum EN AW 5083 after the run in period, see fig. 4. By incorporating silicon in the a-C:H matrix the abrasive wear of the coating leads to an additional formation of silicon containing nanoparticles [15]. In contact with steel the nanoparticles are able to decrease the friction value by interacting with the counter surface or the environment [8, 14]. Thus, the high friction and the extended run-in period are possibly caused by interdependencies between the silicon in the a-C:H matrix, the formation of silicon containing nanoparticles and the aluminum oxide or pure aluminum. The interaction between these factors increases with a higher silicon content.

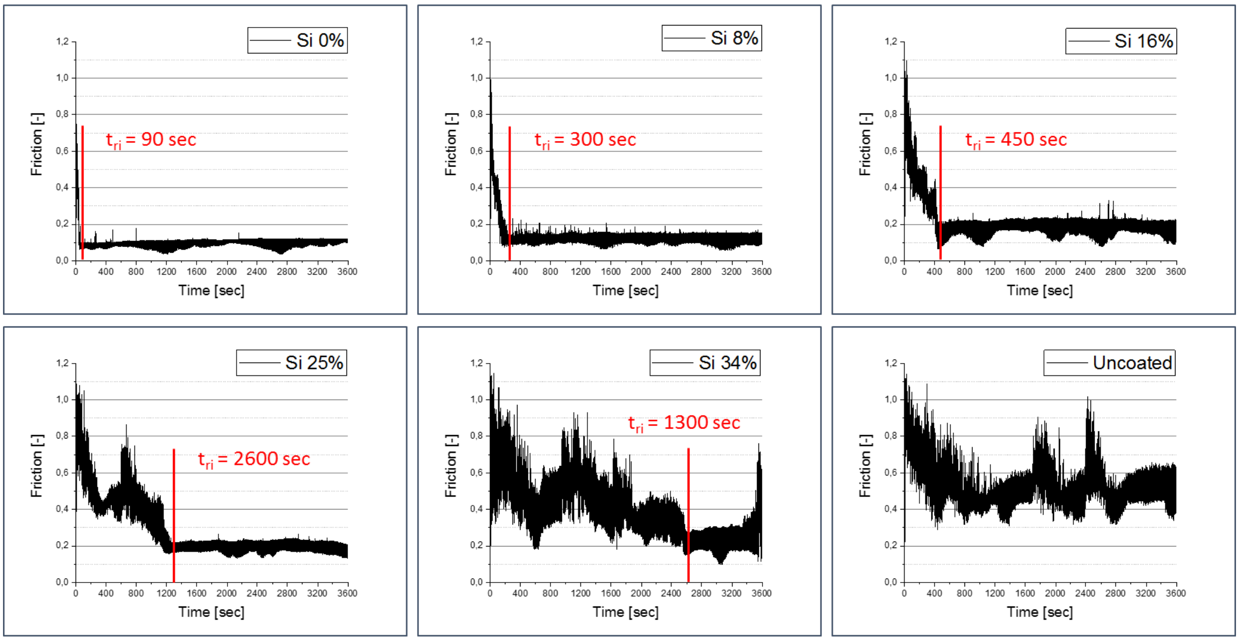


Fig. 5: Average friction development of the coated and uncoated steel balls sliding against aluminum EN AW 5083

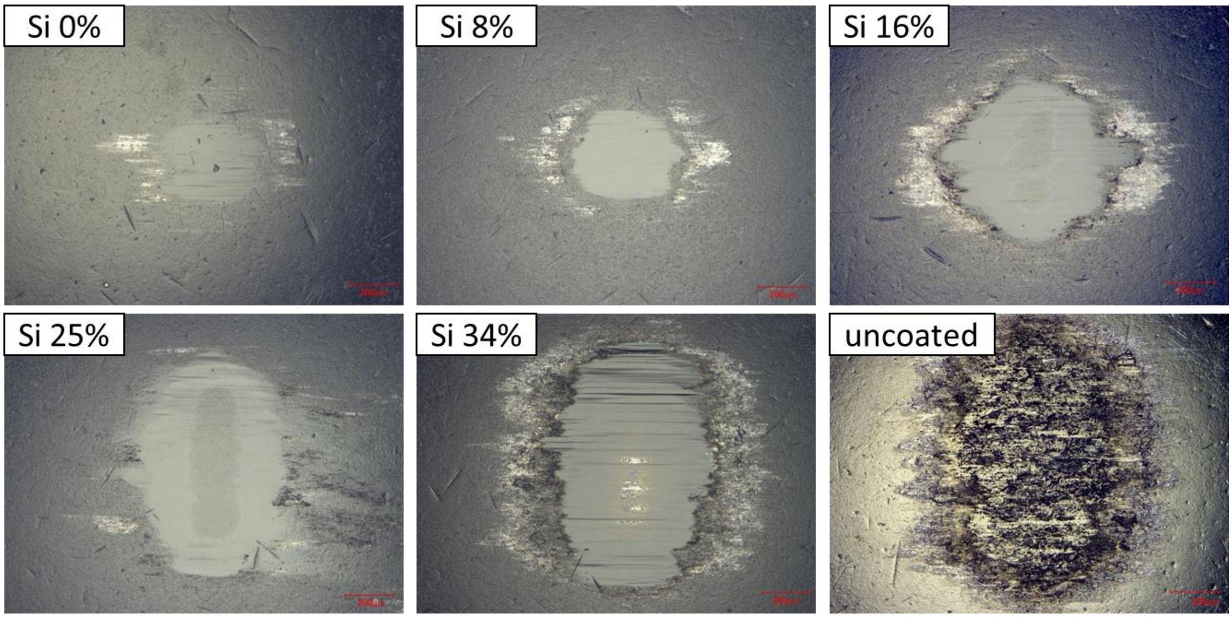


Fig. 6: Wear tracks of the coated and uncoated steel balls after sliding against aluminum EN AW 5083

On all coatings aluminum adhesions were formed around the wear tracks. Scanning electron microscope (SEM) images of the peripheral zone are shown in fig. 8a and 8b for Si8% and Si34%. Regarding the intersection between the wear track and the peripheral zone, a smoothening of the surface is noticeable for both coatings. On the Si8% coating aluminum adhesions were only formed between the asperities in the peripheral zone whereas on the Si34% coating aluminum adhered to the rough surface of the peripheral zone and the smoothed surface in the intersection.

The hardness of a coating measures the resistance against penetration and therefore the resistance against abrasive wear. In contrast to this, there is no correlation between the hardness and the wear of the tested coatings above 16 at.-% silicon, see fig. 9. Furthermore, the removal of the aluminum increases exponential with an increasing silicon content, see fig. 10. Hence, the abrasive wear of the coatings and the aluminum EN AW 5083 was superposed by another wear mechanism based on the incorporation of silicon. This fortifies the thesis of an interaction between the silicon in the a-C:H matrix, the formation of silicon containing nanoparticles and the contacting aluminum.

Due to wear, the contact area between the coated ball and the aluminum sheet increases and subsequent the contact pressure decreases during the tribometer tests. According to the wear values (fig. 9), the contact pressure differs at the end of the run-in period depending on the silicon content. Thus, the contact pressure is another possible factor influencing the tribological behavior of silicon modified a-C:H coatings.


Fig. 7: SEM-image and EDX-mapping of aluminum adhesions on the exposed steel after a partial removal of the Si 34% coating

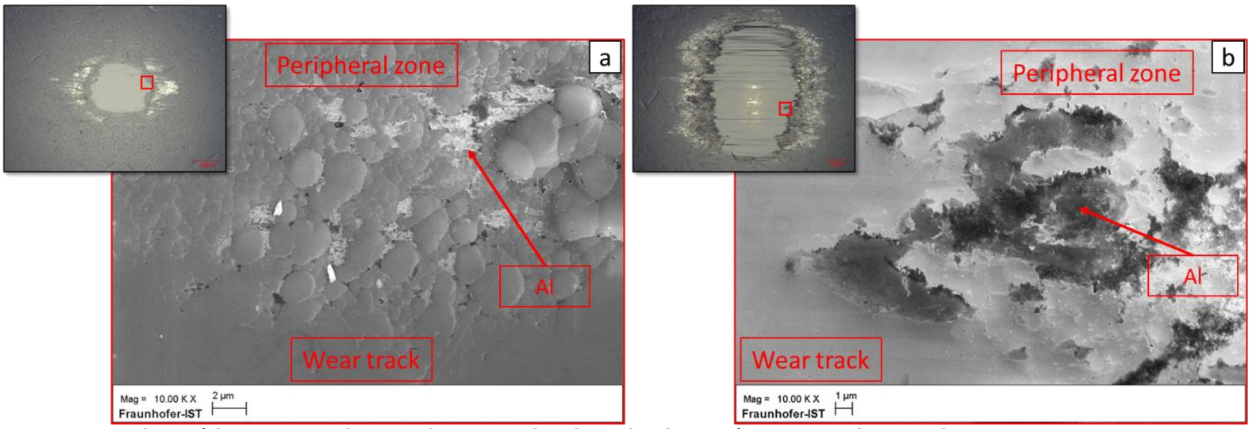


Fig. 8: SEM-analysis of the intersection between the wear track and peripheral zone of Si 8% (a) and Si 34% (b

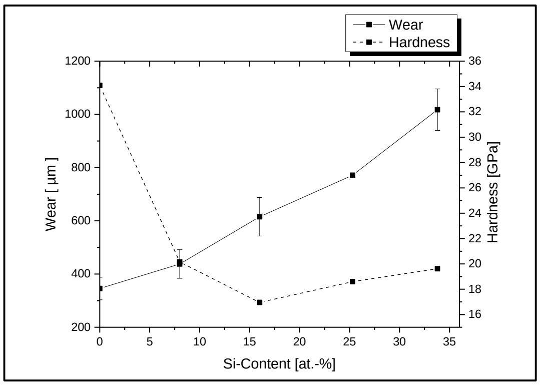


Fig. 9: Average wear and hardness of the tested a-C:H and a-C:H:Si coatings

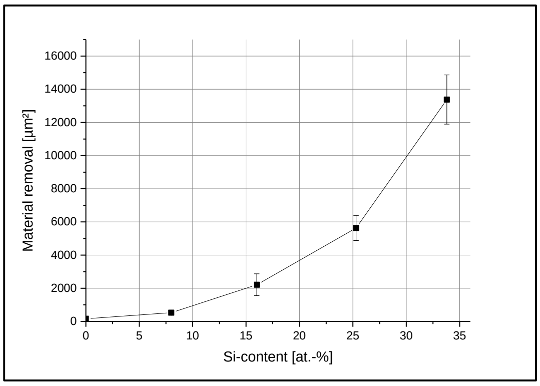


Fig. 10: Average wear of the aluminum EN AW 5083 sheet as a function of the silicon content in the a-C:H:Si coating

## 4 Conclusions

In this paper silicon modified amorphous hydrogenated carbon coatings (a-C:H:Si) were deposited to determine the adhesion tendency against aluminum EN AW 5083 as a function of the silicon content (Si = 0 at.-%, 8 at.-%, 16 at.-%, 25 at.-% and 34 at.-%). Therefore, ball-on-disc tribometer tests and strip drawing tests were conducted, which allow a reproduction of tribological loads with a high proximity to industrial dry forming processes. The following conclusions were made based on the tests results:

1. The adhesion tendency of a-C:H and a-C:H:Si (Si = 8%, 16%, 25% and 34%) coatings against aluminum EN AW 5083 is significantly lower than the adhesion tendency of an uncoated steel surface.
2. The average friction value of the a-C:H:Si coatings after the run-in period rises linear with an increasing silicon content.
3. The run-in duration of a-C:H:Si coatings extends with an increasing silicon content. Differing smoothing processes are a possible explanation for this tribological behavior. The duration and high friction value of the run-in period should be considered for a dry forming process of aluminum EN AW 5083 and is maybe a reason for the distinct formation of aluminum adhesions in the strip drawing tests.
4. The wear amount of the a-C:H:Si coatings and the aluminum EN AW 5083 sheets rises with an increasing silicon content. A non-correlation between the hardness of the coatings and the wear amounts indicates superposing wear mechanisms.
5. An incorporation of silicon influences the tribological behavior of a-C:H coatings sliding against aluminum EN AW 5083. The tribometer tests indicated interdependencies between the silicon and the aluminum which were aggravated by an increase of the silicon content.

Further tests are needed to investigate the interaction between the incorporated silicon in the a-C:H coating and the aluminum EN AW 5083. As a part of this investigation, it is to verify whether the tribological behavior of the tested a-C:H:Si coatings changes in a sliding contact with other aluminum alloys. Clarifying the interactions will lead to a better understanding of the tribological functionality of silicon modified a-C:H coatings and of the adhesion mechanisms in a sliding contact against aluminum EN AW 5083.

## Acknowledgements

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