microparticles. Moreover, the error signal showed the contours of the worn material at the boundaries of the wear marks located across the scanning direction due to a significant change in the Peak Force Setpoint in this scanning area.

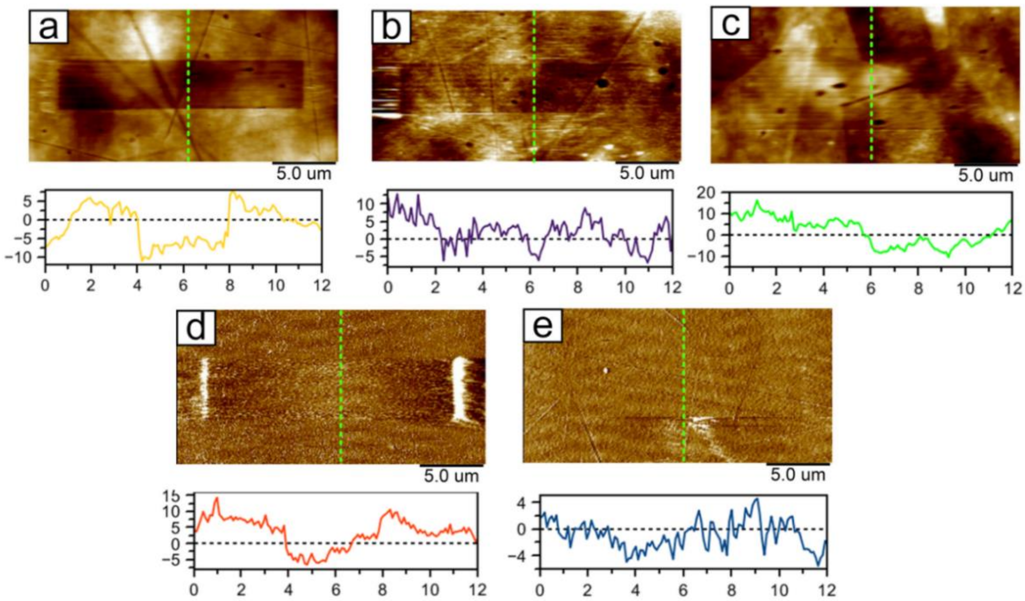

Figure 7. AFM-images of wear test results at loading of 1.164 µN, speed of 2 µm/s, and 100 cycles on the steel substrate and the tantalum coatings: steel (**a**), Ta_2O_5 (**b**), TaON (**c**), TaN (**d**), Ta (**e**).

The dependences of the CoF and *F* of the coatings during the wear in the "plowing" mode to the number of friction cycles are presented in Figure 8. Each point in the obtained diagrams is averaged over 50 scanning lines. "Teeth" in values of CoF are explained by position of the probe in each cycle with respect to the surface and AFM- photodetector: «upper–down» or «down–upper». The higher the value of CoF, the larger the "part" of probe twisting per when changing the position of the probe at reciprocating motion. CoF values were decreased after 15 cycles; it is explained by «breaking-in» to expressed in the change in the subnanometer layer of the material under the tribological load from the start of scanning and its uniform distribution over the surface. CoF in steady-state for steel was 0.448. The coatings TaON, Ta, and TaN allow decreasing CoF of the surface down to 0.444, 0.336, and 0.308, respectively (Figure 8). The deposition of Ta_2O_5 coatings on the steel substrate increases CoF to 0.780.

Specific volumetric wear allows comparing coatings of tantalum and its compounds with other materials quantitatively. All the tantalum coatings under research are capable of reducing the wear of steel (25.4×10^{-13} $m^3/N{\cdot}m$) more than twice (Figure 9). The minimum value of specific volumetric wear were recorded for the Ta coatings— 2.1×10^{-13} $m^3/N{\cdot}m$. TaN and TaON showed the middle values—4.2×10^{-13} and 6.1×10^{-13} $m^3/N{\cdot}m$. The minimum wear were determined for Ta_2O_5 coatings—11.6×10^{-13} $m^3/N{\cdot}m$. The dependences of specific volumetric wear on Ta atomic content in coatings are in good agreement with their CoF (Figure 9). The "plowing" mode allows assessing the real strength properties of the material during the friction.

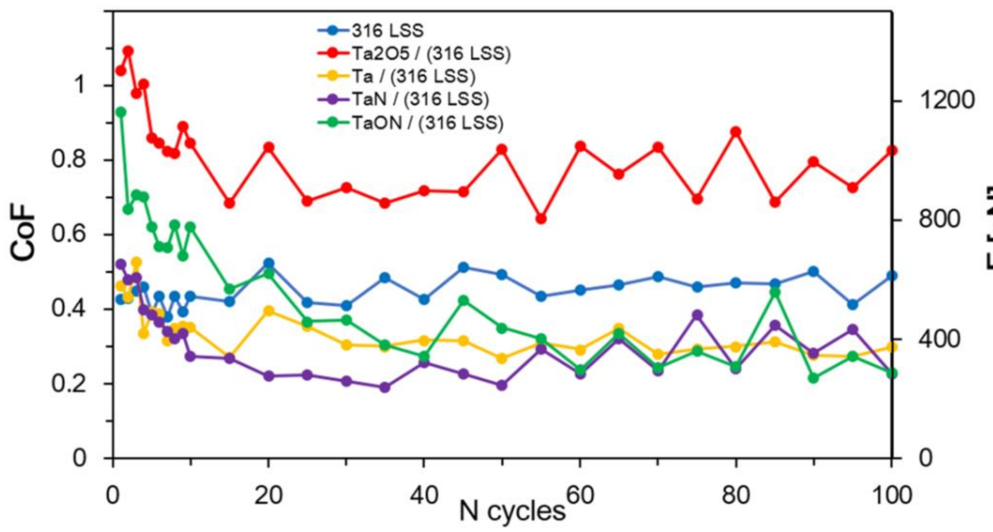

Figure 8. Dependence of the obtained friction coefficients on the number of friction cycles of the studied coatings on the steel substrates.

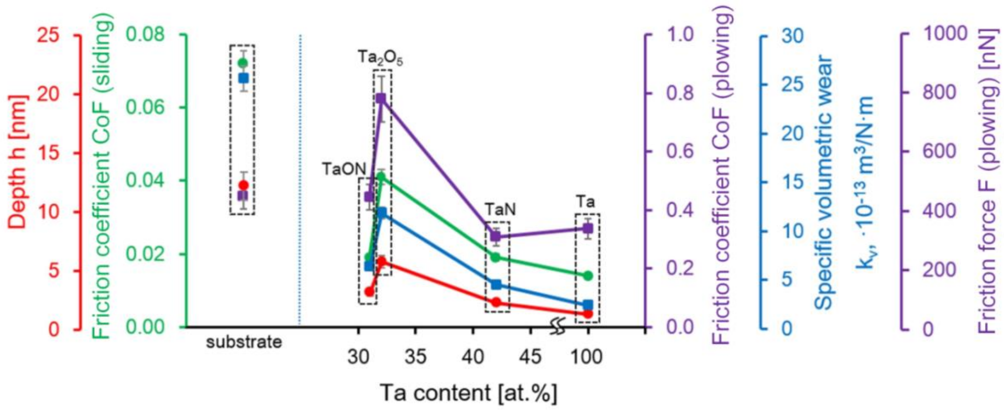

Figure 9. The dependences of h, CoF (sliding), CoF (plowing), k_v, and F of Ta based coatings on the Ta atomic content.

The influence of the adhesive forces is better characterized by the "sliding" mode [60,61]. The determined CoF for stainless steel in the "sliding" mode is 0.072 (Figure 9). After the deposition of nanostructured tantalum coatings, the CoF decreases to 0.014 (Ta) and 0.019 (TaN and TaON). CoF of Ta_2O_5 coatings in the "sliding" mode is 0.041. The dependences of CoF in the "sliding" and "plowing" modes on Ta atomic content in coatings have a similar behavior (Figure 9).

The better tribological properties of Ta coatings can be explained by its microstructure and plasticity of the coating. The low CoF values of the oxynitride film can be explained by the high roughness, and the high values of tantalum oxide, by the low roughness. Microhardness is often considered as the main characteristic to predict the wear. The Ta_2O_5 coatings with the highest H of 18 GPa and R_a of 4.2 nm showed the weakest nanotribological properties. This result can be explained by the significantly different mechanism of wear in the environment of nanofriction contact from usual classical mechanism of macrocontact.

The authors of [35] obtained TaNx coatings by the high-frequency magnetron sputtering method. Tribological researches were carried out by the nanoindentation method using a Berkovich diamond tip at a load of 5 μN. The average friction coefficient was ~0.18. The significant difference between CoF in [35] and those obtained by us for TaN (0.30) is explained by the low applied load during tribological tests of AFM. In [36], tantalum nitride films were synthesized on silicon using magnetron sputtering. A pin-on-disk (alumina ball) tribometer at 1 N load was used to obtain the coefficient of friction and the wear rate