The surface of TaON coatings is characterized by a granular structure with the small crystallites of 5 nm in diameter (inset Figure 4d). The surface of TaN coatings consists of grains of 20 nm in diameter (inset Figure 4e). These grains assembled into chains, which formed the edges of cells 200 nm in size (arrows Figure 4e). R_a values of TaN and TaON coatings on the area 4 × 4 μm were 9.5 and 5.6 nm, respectively.

The obtained morphology of the coatings of tantalum and its compounds makes it possible to explain the numerical values of the roughness.

The obtained results on AFM microstructure of the coatings of tantalum compounds are consistent with the previously published studies of Ta [52] and TaN [53] coatings which had a granular structure. The grain size is significantly smaller and is close to calculations in the research of Alishahi et al. [54].

3.4. The Mechanical Properties of Coatings

The diagrams, showing dependence of the indentation depth on indentation load for the coatings and the steel are demonstrated in the Figure 5. The shape of the curves and their position according to the Y axis show the distribution of coatings by H: the closer the curve is to the Y axis, the harder the material is. The area bounded by the curves of the approach–retraction characterizes the plastic deformation. According to the curves the significant difference in mechanical properties of coatings and substrate is visible.

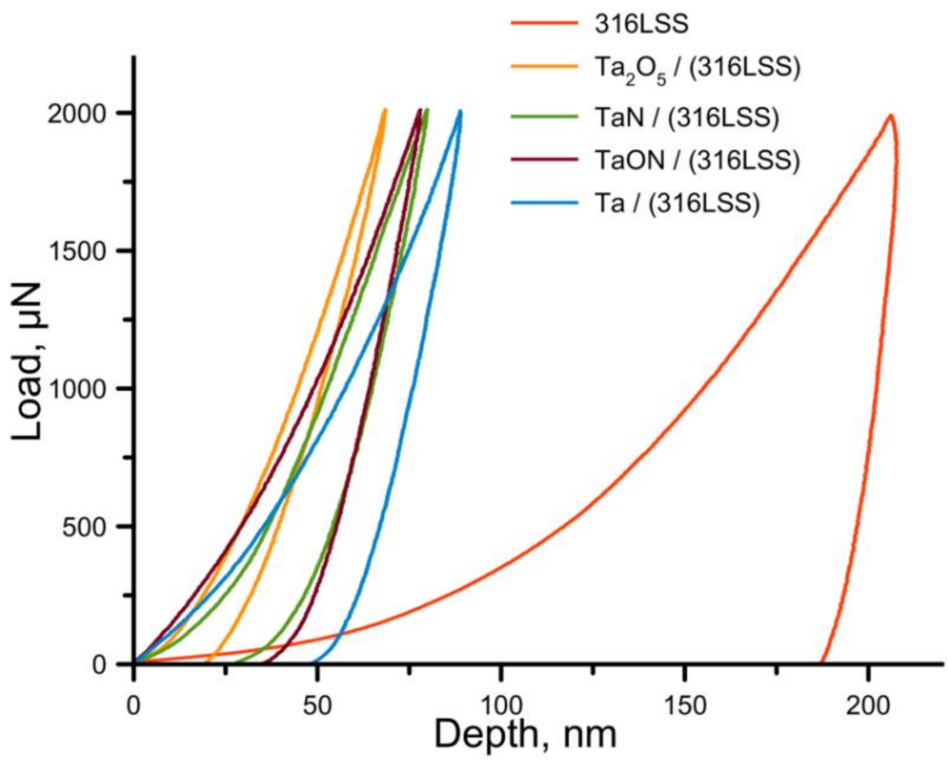

Figure 5. The dependence curves of load on the indentation depth *h*.

It was shown that the values of H and E of stainless steel 316 L SS were determined as 1.7 ± 0.2 and 150.0 ± 10.0 GPa, respectively. Plasticity according to the indentation curve area was the heighest—91.4% and H/E—the lowest—was 0.01. Metallic Ta coatings are characterized by the lowest H of 8.3 ± 0.2 GPa. Nonmetallic addition of O and N increased the value of H to 10.0 ± 0.3 GPa for TaN, 13.3 ± 0.6 GPa for TaON, and 16.0 ± 3.5 GPa for Ta_2O_5. The values of the elastic moduli of four studied coatings on the stainless steel substrates are about 158.0 GPa. These values are close to E of 156 GPa and H of 10 GPa for bulk pure Ta, obtained and described by Kommel et al. [55]. After the coatings' deposition, the strength of the steel substrate increased and H/E allows to estimate by how much:

0.05 for Ta, 0.06 for TaN, 0.08 for TaON, and 0.10 for Ta_2O_5. The coatings on stainless steel substrates (304 SS), formed via reactive magnetron sputtering by the authors of [56], showed lower mechanical properties for coatings of Ta compounds: for Ta_2O_5—H of 5.8 GPa, E of 135 GPa, and H/E of 0.049 and for TaON—H of 7.5 GPa, E of 119 GPa, and H/E of 0.056. The reason of the underestimated values of H and E in [56] may be the lower content of Ta in the coatings in comparison to those studied in this work. In [57], for coatings of 700–100 nm thickness, the values of E were 127 GPa for Ta and 108 GPa for Ta_2O_5, and the values of H—6.8 GPa for Ta and 8.4 GPa for Ta_2O_5. The somewhat underestimated values of the characteristics can be explained by the excessive indentation depth and the influence of the substrate.

The dependences of the mechanical properties of investigated coatings on the atomic content of Ta are shown in Figure 6. The higher oxygen and nitrogen content in the coatings based on Ta, the greater the microhardness of the surface. This tendency is associated with the introduction of oxygen and nitrogen atoms into the tantalum crystal structure, what leads to compressive residual stress in the coatings [58]. In addition, the authors of work [59] found that the higher the oxygen content, the higher the average hardness.

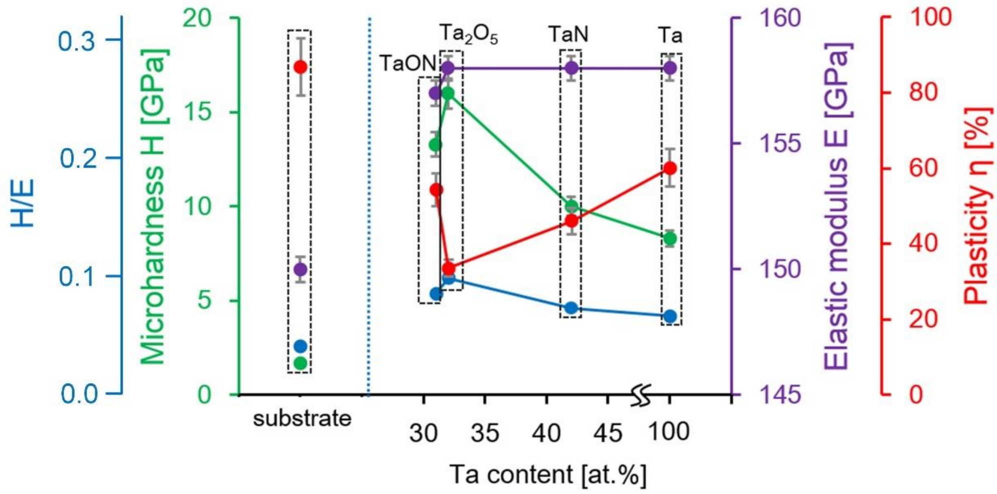

Figure 6. The dependences of H/E, H, E and η of Ta based coatings on the Ta atomic content.

On the base of the dependence of E and H on the atomic content of Ta coatings on the steel (Figure 6), the Ta content in the coatings does not affect the elastic modulus but affect the hardness. Such effect was described in [55] where two existing polytypes of tantalum α-Ta and β-Ta showed the same E of 188 GPa and the different H: 10 GPa for α-Ta and 18 GPa for β-Ta. The discrepancy in the values of E and H can be explained by the film thickness (of 100 and 300 nm), which is usually higher for thin films.

Taking into account the whole set of physical and mechanical characteristics of Ta coatings and its compounds, TaON is the optimal coating, which simultaneously has sufficient hardness and high plasticity.

3.5. The Tribological Characteristics

The results of friction and wear tests in the "plowing" regime are shown in Figure 7. Wear tracks on TaON and Ta coatings are visible only in the Friction regime. These tracks show the efficacy of Ta based coatings of wear protection of steel. Wear tracks on TaN (Figure 7d) and Ta (Figure 7e) coatings are visible only in the PeakForce Error data type. Since PeakForce QNM uses Peak Force as the feedback signal, the PeakForce Error data type is essentially the Peak Force Setpoint with the error. It is recorded simultaneously with the topography. In this mode, the boundaries of the wear mark are better visible. We had to use the error signal as the wear on these materials was very low. The topography mode did not allow it to be visualized against the background of scratches and protruding