

Article

Abrasive Wear Characteristics of 30MnB5 Steel for High-Speed Plough Tip of Agricultural Machinery in Southern Xinjiang Region

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Abstract: The high-speed plough tip is the core soil-touching component in southern Xinjiang field cultivation, but the interaction of the plough tip with the soil results in severe wear of the tip. The friction behaviour of sand and soil on plough tips was investigated with a homemade rotary abrasive wear tester in a one-factor multilevel test with three parameters: moisture content, velocity/rotational speed and friction distance. The objective was to study the friction behaviour of the sand soil and plough tip and analyse and characterise the wear amount, wear thickness and compressive stress distribution, three-dimensional wear morphology and microscopic wear morphology of the plough tips. The results show that with increasing speed, the wear amount changes more gently; with increasing soil water content, the soil adhesion force and lubricating water film increase so that the wear amount follows a second-order parabolic law; and with increasing friction distance, the wear amount gradually increases, and the wear rate also shows an upward trend when the plough tip is in the abrasive wear stage. The tip makes contact with the firmer soil with higher surface compressive stresses, causing the most wear. As the friction distance increases, sand particles become embedded in the contact surfaces, creating a groove effect along with spalling pits caused by fatigue wear. During the whole wear period, the groove effect is always accompanied by spalling pits appearing repeatedly. The analysis of the wear micromorphology of the plough tip shows that the number of flaking pits gradually decreases in the direction of soil movement, and the form of damage changes from impact wear to plough groove scratches. Abrasive wear interacts with corrosive wear to exacerbate plough tip wear.

Keywords: southern Xinjiang; sandy soil; high-speed plough tip; 30MnB5 steel; three-body abrasive wear



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1. Introduction

South Xinjiang is an important crop production area in China, belonging to the oasis agriculture type [1–3]; the main crops grown are cotton, maize and wheat [4,5]. However, the high saline content of the soil, sandy soil and soil sloughing have a greater impact on the absorption of water and fertilisers in the soil by plants [6–8]. Tillage is the primary process in agricultural planting activities, which can increase the interaction between soil and air, improve water storage capacity, break the phenomenon of soil crusting, provide a good growing environment for crops, and promote the sustainable development of agriculture [9–11]. High-speed plough tips are the core component in deep tillage operation in Xinjiang's large fields, but the plough tip faces friction wear and impact during tillage, bringing about plough body loss, reduced working efficiency and increased energy consumption, which result in a large number of economic losses. With the rapid development of agriculture, the friction performance of the plough tip components has

put forward higher requirements, and the examination of its wear resistance in soil is a necessary part of the optimisation of plough tip design and material selection [12].

High-speed plough tips are subjected to harsh tillage environments and to frictional wear from soil particles and crop residue, resulting in a loss of plough tip material. This loss is dominated by low-stress three-body abrasive wear and is accompanied by shock and vibration [13]. In actual tillage, the interaction behaviour of the plough tip with the soil is complex and influenced by various factors, for example, the environmental media [14–17], the material and structural properties of the components [18–22] and the tillage working conditions [23,24]. And the various factors are coupled with each other. Therefore, it is very difficult to pre-determine the exact value of the friction coefficient and comprehensively estimate the effects of various factors.

The clear single-factor friction mechanism of components has become the focus of research, and scholars in this field have conducted a large number of experimental investigations on this. Kalácska et al. [25] tested 27MnB5 steel plough tips by conducting field wear tests to analytically characterise the changes in mass, hardness and microstructure, used 3D optical profilometry to obtain the wear contours and measured the changes in line dimensions. The results of the tests showed that the microscopic wear mechanisms of the cutting edges were classified into micro-cutting and micro-ploughing. The microscopic mechanism of the wear was demonstrated by calculating the degree of wear scratches' penetration. Ulbrich et al. [26] used the rotating bowl method to determine the wear of 22MnCrB5 steel specimens (heat-treated and non-heat-treated) in sandy soils. The results showed that the resistance of heat-treated 22MnCrB5 steel to abrasive wear was three times higher than that of non-heat-treated steel. In addition, an instrument developed based on Ulbrich's work allows the measurement of wear during friction and corrosion interactions. The results show that the wear trace of heat-treated 22MnCrB5 steel is about 7.03 μm and that of non-heat-treated 22MnCrB5 steel is about 12.11 μm . The described heat-treatment method improves the resistance to abrasive wear and corrosion of boron steel. Marani et al. [27] used slider tests to study the friction and adhesion coefficient of materials (SST37 carbon steel plate, galvanised steel, glass fibre, titanium nitride coating, tantalum carbide coating) and soils (sandy loam, clay, clayey loam) at different moisture contents (10, 20, 30 and 40%) and sliding velocities (0.1, 0.2, 0.3 and 0.4 m/s). It was found with the different test materials that the adhesion and external friction angles increased with increasing water content for all three soil textures, and the friction and adhesion coefficients increased with increasing sliding velocity. Vaz et al. [28] compared the performance of CGS-MAM martensitic ageing and HVOF metal–ceramic coatings in abrasion, sliding, jet erosion and corrosion tests, where the WC-12Co coating deposited on carbon steel by high-velocity oxy-fuel (HVOF) resulted in more than a 30 times reduction in the downward abrasion wear rate and more than a 100 times reduction in sliding wear and water erosion rates.

In this paper, a one-way multilevel test was carried out by means of a homemade rotary abrasive wear tester with soil water content, rotational speed and friction distance as the influencing factors. This study aimed to analyse and characterise the wear amount, wear thickness and compressive stress distribution, three-dimensional wear morphology and microscopic wear morphology of plough tips and to investigate plough tip wear characteristics under the influence of various factors. The results of this study can provide a theoretical basis for high-speed plough structure design, optimisation and material selection.

2. Materials and Methods

2.1. Plough Tip Parameters

In this paper, the plough tip used is adapted to the LK500 high-speed hydraulic turning plough (Ryken Agricultural Machinery (Qingdao) Co., Ltd., Qingdao, China), which has a wide range of uses in the southern Xinjiang region, as shown in Figure 1a. The plough tip material is 30MnB5 steel, which is pressed and moulded. It was quenched at 850 °C using cold oil and then tempered at 500 °C using cold oil. The surface hardness was brought to 442.37 HV. To increase the wear resistance, a surfacing layer was added to the non-working

side of the plough tip to form the first type of self-sharpening, as shown in Figure 1b. The proportions of the main elements and the important mechanical properties of the plough tips are shown in Tables 1 and 2.

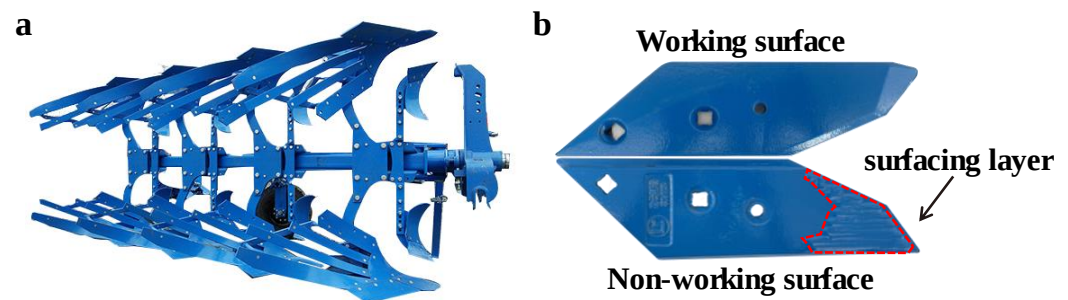


Figure 1. (a) LK500 high-speed hydraulic turning plough; (b) plough tip.

Table 1. Chemical compositions (mass %) of 30MnB5 plough tip.

Element	C	Mn	P	S	Si	Cr	Ni	B
Content	0.32–0.38	1.4	0.03	0.03	0.17–0.37	0.3	0.3	0.0008–0.0035

Table 2. Mechanical properties of 30MnB5 plough tip.

Material	Hardness (HV)	Elasticity Modulus (GPa)	Mass Density (g/cm ³)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
30MnB5 steel	≥550	222	7.85	≥930	≥735	≥10

2.2. Soil Parameters

The sampling point was located in the cultivated area of the regiment in Alar City, and soil parameters were determined at different tillage depths. For example, firmness, density, water content, bulk weight, pH, and the other results are shown in Table 3 [29]. The percentage of sand particles with a particle size of less than 0.2 mm ranged from 84.51 to 87.20% [30]. The wear test was carried out using sand particles with a grain size of less than 0.2 mm, and to eliminate the influence of the loose structure of the soil on the test, the soil was compacted using a roller before the experiment.

Table 3. Field soil parameters.

Tillage Depth (cm)	Firmness (kPa)	Density (g/cm ³)	Water Content (%)	Bulk Density (g/cm ³)	pH
0	274.3	1.39	8.68%	1.27	5.91
10	595.17	1.43	9.01%	1.3	6.19
20	658.37	1.55	10.01%	1.39	6.27
30	1006.1	1.61	9.74%	1.45	6.12
40	1456.07	1.72	9.27%	1.56	6.17

Discrete-element simulation tests require the setting of simulation parameters between soil and soil and between soil and materials in contact with the soil. Combined with relevant data from Lei [31], the main parameters used for the simulation tests are shown in Table 4. Since soil is a complex inhomogeneous material, the reliability of the simulation results depends on the choice of eigenrelationships. The Hertz–Mindlin theory with the JKR contact model was selected for DEM simulations. In order to reduce the computing power of the computer while ensuring a realistic simulation of the tillage process of the high-speed plough as well as the accuracy of the calculations, the radius of the soil particles

was set to be 5 mm, and a soil model with a size of $1.8 \text{ (L)} \times 1.2 \text{ (W)} \times 0.5 \text{ (H)} \text{ m}^3$ was established. To match the speed of the wear test, the simulated running speed was 2 m/s, as shown in Figure 2.

Table 4. Main material properties used in the DEM simulation.

Parameter	Value	Source
Particle radius (mm)	5	[31]
Poisson's ratio of soil	0.3	[31]
Shear modulus of soil (Pa)	1.1×10^6	[31]
Density of soil particles (kg/m^3)	1465	measured
Coefficient of restitution for soil–soil	0.25	measured
Coefficient of static friction for soil–soil	0.67	measured
Coefficient of rolling friction for soil–soil	0.2	measured
JKR surface energy (J/m^2)	6.1	measured
Coefficient of restitution for soil–steel	0.43	measured
Coefficient of static friction for soil–steel	0.39	measured
Coefficient of rolling friction for soil–steel	0.1	measured
Wear constant (m^2/N)	4×10^{-13}	[31]

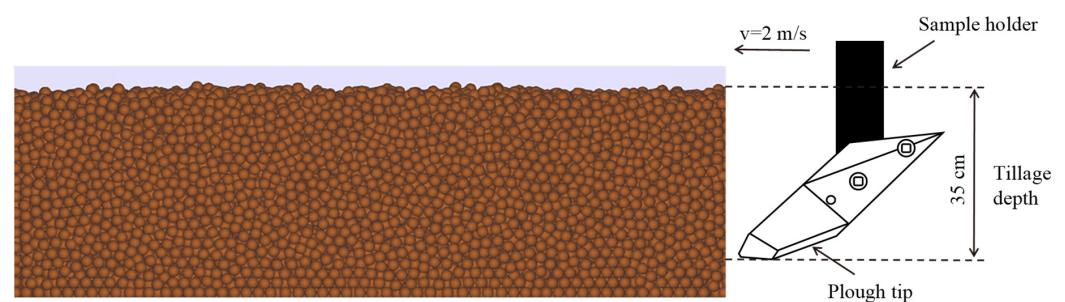


Figure 2. Schematic diagram of discrete-element simulation.

2.3. Wear Test

Wear tests were conducted on a bespoke rotary abrasive wear tester, as illustrated in Figure 3. The sand in the rotating bowl was 35 cm in depth, simulating the tillage depth of the plough tip in the field. The push angle was set at 38° and the mounting angle at 26° , and the plough tip was mounted on the sample frame with a friction radius of 30 cm. The rotary axis drove the plough tip and the suppression roller to make clockwise movements, whereby the plough tip loosened the sandy soil, and the suppression roller then compacted the loosened soil. This process was repeated to conduct the tests. The experiment was carried out by changing the movement speed of the plough tip, the soil water content and the friction distance to carry out single-factor multilevel experiments, and the detailed experimental parameters are shown in Table 5. Each set of experiments was repeated three times using a new plough tip to ensure the accuracy of the results. The tip of the plough was cut into $20 \times 10 \text{ mm}$ samples. Used to characterise the wear characteristics and cross-sectional microchanges in the sample touching the soil surface, the plough tip sample is shown in Figure 3d.

Table 5. Test factor-level table.

Factors	Level 1	Level 2	Level 3	Other Conditions
Speed v /(r/min)	20	30	40	$c = 21\%$, $l = 113 \text{ km}$
Water content $c/\%$	7	14	21	$v = 30 \text{ r/min}$, $l = 113 \text{ km}$
Friction distance l/km	113	226	339	$c = 21\%$, $v = 30 \text{ r/min}$

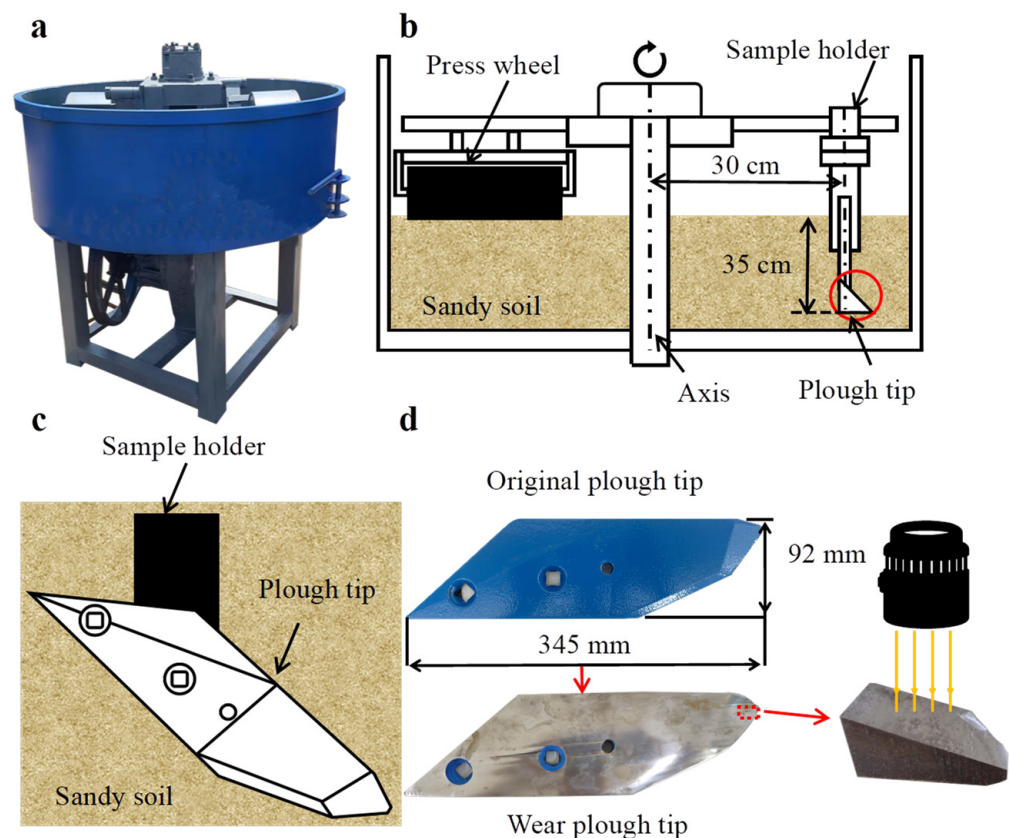


Figure 3. (a) Rotary abrasive wear tester; (b) structure of the tester; (c) principle of plough tip wear; (d) worn plough tip and sample.

2.4. Test Instruments

The plough tips were cleaned using ethanol and ultrasound before and after the test. An analytical balance with a resolution of 0.01 g (LQC-30002, Suzhou Zhengfeng Electronic Technology Co., Ltd., Suzhou, China) was used to measure the mass of the plough tips before and after the test. The plough tips were modelled in a 3D mesh using a 3D scanner (HandySCAN 300, CREAFORM Ltd., Lévis, QC, Canada). The model was optimised by PolyWorks 2022 to obtain the change values for the plough tip thickness. A white light interferometer (SuperView W1, Shenzhen Zhongtu Instrument Co., Ltd., Shenzhen, China) was used to obtain the 3D wear profile of the plough tip sample. A scanning electron microscope (Apreo 2 High-Resolution Field Emission Scanning Electron Microscope, Thermo Fisher Scientific, Dreieich, Germany) was used to carry out the morphological and energy spectrum analyses of the wear surface of the plough tip sample.

3. Results and Discussions

3.1. Wear Volume Analysis

As speed increases, there is a smaller effect on the wear amount of the plough tip, which shows a slight upward trend. The wear of the plough tips at 20 r/min and 30 r/min was 5.56 g and 12.71 g. As soil water content increases, it has a greater effect on the wear of the plough tips, with a second-order parabolic pattern of increasing and then decreasing wear. The plough tip wear at 14% water content was 35.89 g. As the friction distance increases, it has the greatest effect on the wear of the plough tip, which shows a clear upward trend. The plough tip wear at 113 and 339 km was 35.89 and 160.32 g, respectively. The effect on plough tip wear follows the pattern friction distance > soil water content > rotational speed, as shown in Figure 4.

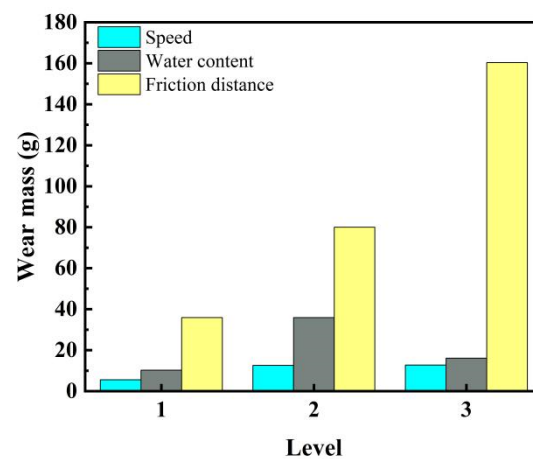


Figure 4. Plough tip wear amount.

The phenomenon of a slight change in the coefficient of friction with speed is similar to the results of a test conducted by Esteves [32]. The test was set up with a small rotational speed interval, and the heat generated by friction was dissipated through the evaporation of moisture from the ground and air circulation without causing a large accumulation of frictional heat. The metal did not produce annealing and tempering effects, so the wear changes were more moderate. However, the kinetic energy of the abrasive in contact with the metal increased as the speed increased, causing a slight increase in wear.

It is widely accepted that the variation pattern of adhesion force with soil moisture essentially adheres to the classical second-order parabolic law [15]. At low water content, as soil water content increases, soil adhesion increases, making it difficult for soil particles to move. When the soil water content is less than 14%, the increase in water content and the increase in soil adhesion show increased plough tip wear. When the soil water content exceeds 14%, a thicker film of lubricating water slows down the plough tip wear, but the amount of wear remains high.

Changes in wear patterns caused by friction distance or friction time can be divided into three stages: the break-in wear stage, the steady wear stage and the severe wear stage. The wear rates in the three stages range from increasing to gradually moderating to sharply increasing. In this paper, the wear amount increases gradually with increasing friction distance, and the wear rate also shows an increasing trend. This indicates that the plough tips are in the break-in wear stage over a friction distance of 339 km.

3.2. Wear Thickness and Surface Pressure Analysis

A three-dimensional grid model of the original and 339 km worn plough tips was fitted to calculate the deviation value for the touchdown surface of the plough tip. The deviation values were set to 0–2 mm (blue), 2–4 mm (green) and 4–6 mm (red), as shown in Figure 5a. The results of the DEM simulation used to simulate the compressive stress distribution on the plough tip surface during ploughing are shown in Figure 5b. As can be seen in Figure 5a, the heavily worn area (red) occupies the tip of the touchdown surface and extends inwards. As the plough tip stands obliquely in the soil, the soil firmness when in contact with the soil decreases from the tip to the end of the plough. The red area represents where the tip is in contact with soil of higher solidity, where the tip of the tillage has a cutting and squeezing effect on the soil and the stress is most concentrated, as shown in Figure 5b. The light areas of wear (blue, green) are concentrated at the rear end of the plough tip and at the edge positions, which are in contact with less firm soil with less interaction force with the soil; therefore, the wear is lighter. Overall, the most tip wear occurs during tillage due to compression by the soil, resulting in higher surface compressive stresses. Variations in part thickness were also demonstrated in studies by Cucinotta and Natsis [33,34].

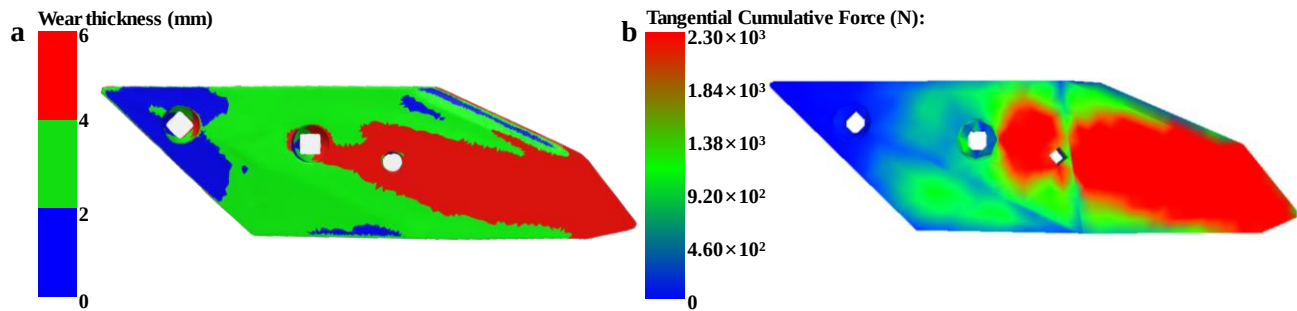


Figure 5. (a) Plot of wear thickness deviation of the plough tip. (b) Plot of compressive stress distribution on the surface of the plough tip.

The plough tip wear is concentrated in the tip portion, and a plough tip projection contour variation diagram is obtained, as shown in Figure 6. In the figure, the purple contour is the original contour, the edge of the cutting edge is smooth and flat and the cutting-edge joint is sharp and angular. When the friction distance is changed from 0 to 339 km, it can be seen that the projected area of the tip decreases, the cutting edge gradually becomes rugged due to material spalling and the corners of the cutting-edge joint become rounded. At the same time, the length and width of the tip also decrease.

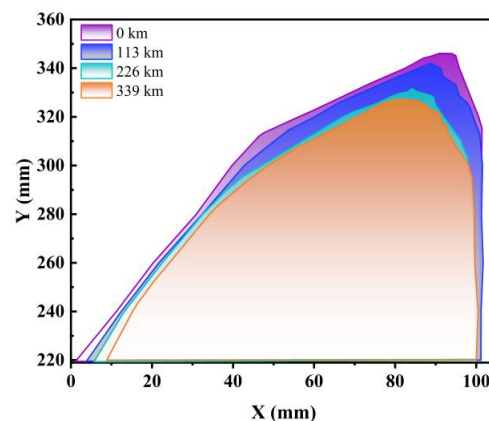


Figure 6. The plough tip projection variation diagram.

3.3. Three-Dimensional Wear Morphology Analysis

A three-dimensional morphology analysis of the wear surfaces of plough tip samples with the original morphology and friction distances of 113, 226 and 339 km simulated for different lengths of time at the same location is shown in Figure 7. Two-dimensional contour curves of part of the region of Figure 7c,d were obtained, as shown in Figure 7e,f. It can be seen from Figure 7a that the original surface caused by machining is high and low with no distinctive features, and the roughness (S_a) is $6.416 \mu\text{m}$. It is possible to observe a large number of spalling pits as well as a large number of continuously intersecting plough grooves with a roughness (S_a) of $0.818 \mu\text{m}$ in Figure 7b. Under high-water-content conditions, soil particles tend to move randomly on the plough tip surface, creating randomly orientated groove scratches. The same phenomenon was observed in a study by Singh et al. [35]. Yao et al. [30] found that component wear can be reduced when the soil water content is high. It can be observed from Figure 7c that there are a large number of dense and inconsistent width furrows as well as a small number of spalling pits at the tip of the plough tip with a roughness (S_a) of $0.612 \mu\text{m}$. It can be observed from Figure 7d that the number of surface spalling pits is reduced and their size decreases with a roughness (S_a) of $0.427 \mu\text{m}$. Coronado [36] and Kalácska [25] verified by experimental comparisons that measuring the width and depth of the grooves calculates the D_p value, which informs about the microscopic wear mechanism of the surface. The D_p value of the plough groove was

calculated by obtaining a 2D profile curve of the wear surface, as shown in Equation (1) [29]. For different depths and widths of grooves, when the D_p value is greater than 0.2, the wear mechanism is micro-cutting, and when the D_p value is less than 0.2, the wear mechanism is micro-ploughing. At 113, 226 and 339 km, the D_p values on the surface of the plough tip samples were less than 0.2, and the wear mechanism was micro-ploughing, as shown in Figure 7e,f. The sand soil used in the experiment has a small particle size; the wear surface roughness gradually decreases; and the soil has a polishing effect on the plough tip surface. Overall, as the friction distance increases, the machined bumps on the plough tip surface are gradually worn away, and sand particles are embedded into the contact surface, creating a plough groove effect, along with spalling pits caused by fatigue wear. Throughout the wear period, the plough groove effect is always accompanied, and the spalling pits appearing reciprocally.

$$D_p = \frac{R_z}{\frac{R_{sm}}{2}} \quad (1)$$

where R_z is the average height of ten points on a single trench, μm ; R_{sm} is the average spacing on a single trench, μm .

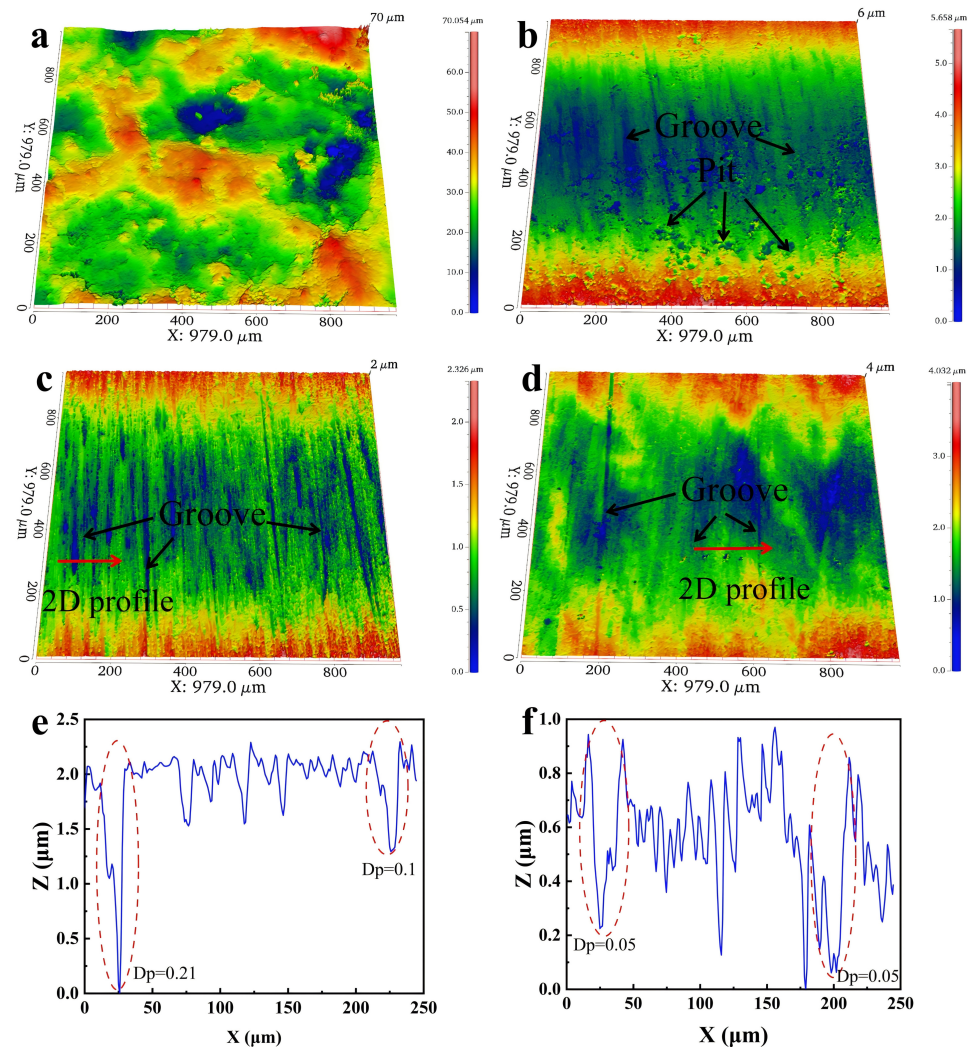


Figure 7. Three-dimensional wear topography for different friction distances: (a) original surface; (b) 113 km; (c) 226 km; and (d) 339 km. (e) Two-dimensional cross-section curves for 226 km 3D wear surface; (f) 2D cross-section curves for 339 km 3D wear surface.

3.4. Microscopic Wear Morphology Analysis

The wear surface of the plough tip sample with a friction distance of 339 km was observed in the extended soil sliding direction, as shown in Figure 8. It can be seen from Figure 8a that the plough tip edge profile becomes rough due to material loss caused by abrasion, while there are impact pits caused by interactions with soil particles on the edge surface as well as plough furrows, with a high percentage of impact pits, with impact wear dominating at the cutting edge. The extended soil sliding direction shows a decrease in the number of impact pits and a gradual change in furrow scratches, as shown in Figure 8b. Subsequently, the form of damage to the plough tip surface by the soil particles gradually changed to predominantly furrow scratches with a small number of spalling pits, as shown in Figure 8c. Similar results were found in studies by Kalácska and Bialobrzeska [25,37]. In addition to this, ring-shaped indentations formed on the metal surface after rotational crushing of the soil particles were observed, as shown in Figure 8d. Also, tooth marks were formed on the metal surface after rolling abrasion of soil particles, as shown in Figure 8e. Overall, in the soil movement direction, from the plough tip cutting edge to the plough tip surface interior, the form of damage changed from impact abrasion to plough furrow scratches.

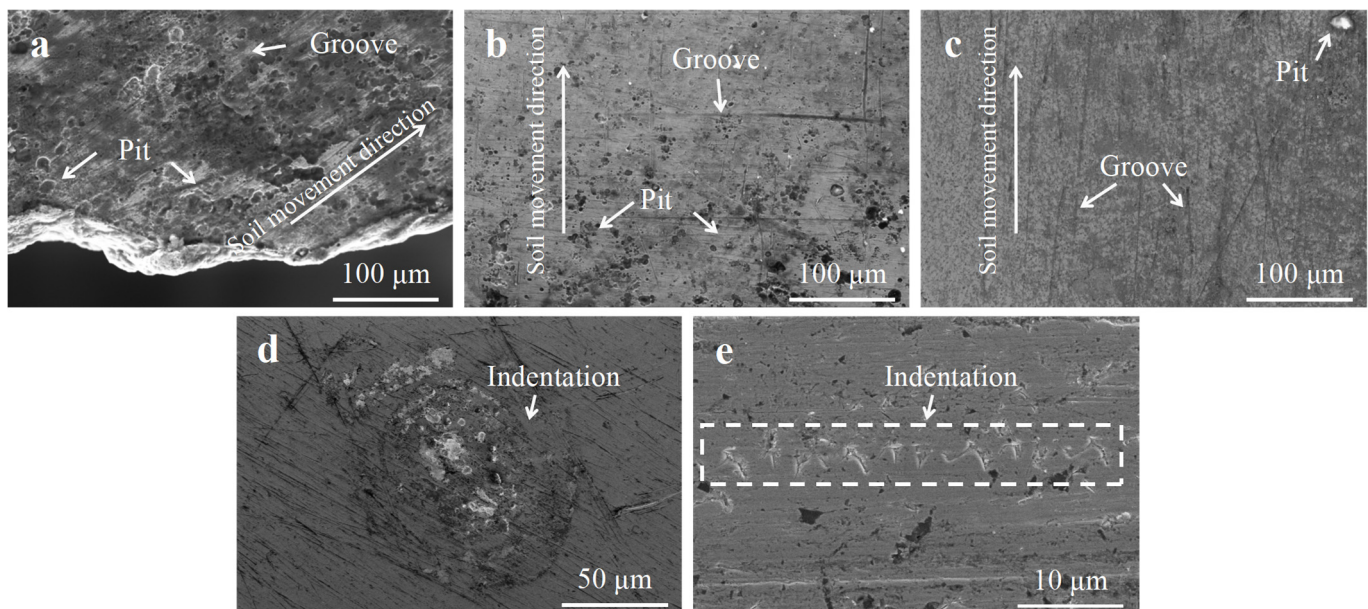


Figure 8. Wear surfaces: (a) cutting edge; (b) middle of the sample; and (c) top of the sample. (d) Soil grain indentation; (e) soil grain rolling tooth marks.

In addition to abrasive wear, traces of corrosive wear were found on the metal surfaces. Under wet conditions, the soil reacted chemically with the metal, as shown in Figure 9. In Figure 9a, small particles can be observed adhering to the metal surface and are darker in its vicinity. Local magnification of Figure 9a gave rise to Figure 9b,c. In Figure 9b, small particles can be observed as crystals, and EDS analysis was performed at the red circle position. The result is shown in Figure 9d, and the crystals were NaCl salt crystals. In Figure 9c, it can be observed that the metal surface chemically reacts with NaCl. EDS analysis was performed at the red circle position, and the results are shown in Figure 9e, with the composition mainly comprising FeCl_3 , FeCl_2 , Fe_2O_3 and Fe_3O_4 . In the test, the abrasive wear and corrosive wear interacted, which aggravated the plough tip wear. Similar results were found in Yao's study [30].

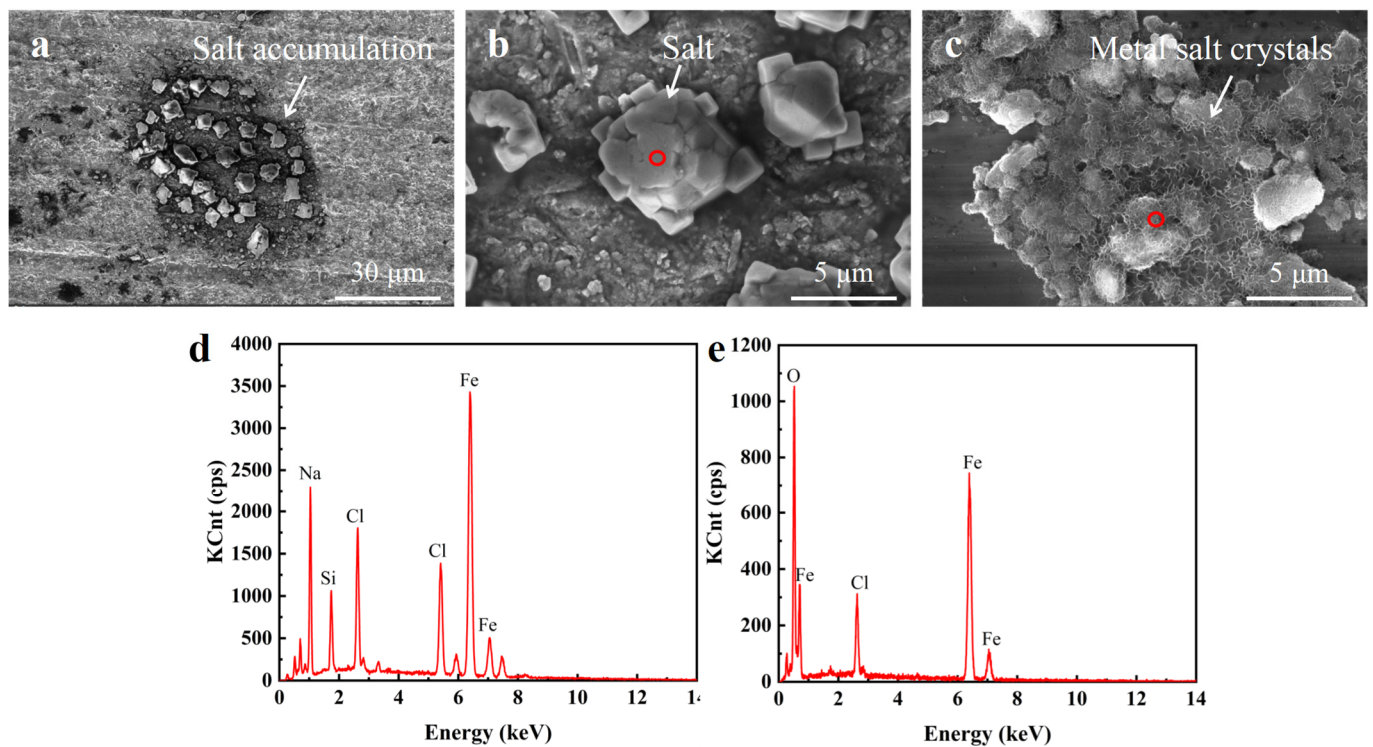


Figure 9. Corrosive wear and EDS analysis of (a) salt accumulation; (b) crystals; and (c) corrosion traces; (d) analysis of the composition of the crystals; (e) analysis of corrosion products.

4. Conclusions

In this paper, through the homemade rotary abrasive wear tester, we investigate the change rule for the plough tip with soil water content, rotational speed and friction distance; analyse and characterise the plough tip's wear amount, wear thickness and surface pressure, 3D wear morphology and microscopic wear morphology; and come to the following conclusions:

- (1) The effect on plough tip wear follows the pattern friction distance > soil water content > friction speed.
- (2) In tillage, the tip undergoes the most wear as it is squeezed by the soil, resulting in high surface compressive stress.
- (3) During the entire wear period, the plough groove effect is always accompanied by spalling pits appearing reciprocally.
- (4) The number of spalling pits gradually decreases from the plough tip edge to the inner surface of the plough tip, and the form of damage changes from impact wear to plough groove scratches.
- (5) Abrasive wear interacts with corrosive wear to exacerbate the plough tip wear.

Author Contributions: X.H.: conceptualisation, methodology, investigation, formal analysis, writing—original draft. Q.Y.: software, data curation, investigation, writing—original draft. M.L.: software, validation. Z.G.: visualisation, investigation. P.F.: visualisation, investigation, writing—review. L.Z.: funding acquisition, project administration. Y.Z.: conceptualisation, funding acquisition, resources, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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