Effects of self-healing biomimetic subsoiler on tillage resistance, wear-corrosion performance and soil disturbance morphology under different soil types

Yueming Wang[1], Chenjie Lu[1], Jing Chen[2], Chenhuan Cui[3], Yijie Pan[4], Wilhelm Pfleging[5], Jiyu Sun[6*]

(1. *School of Engineering, Huzhou University, Huzhou 313000, Zhejiang, China*;
2. *Liaoning Provincial Institute of Agricultural Mechanization, Shenyang 110161, China*;
3. *School of Information and Electrical Engineering, Hangzhou City University, 51 Huzhou Street, Hangzhou 310015, China*;
4. *FUSTEEL Co., Ltd, Huzhou 313000, Zhejiang, China*;
5. *Institute for Applied Materials – Applied Materials Physics, Karlsruhe Institute of Technology, Karlsruhe 76344, Germany*;
6. *Key Laboratory of Bionic Engineering (Ministry of Education, China), Jilin University, Changchun 130022, China*)

Abstract: Subsoiling has been widely used all over the world as an important operation method of no-tillage farming. For energy-saving and life-extension, the tillage resistance and wear-corrosion of subsoilers have attracted wide attention. In this study, the tillage resistance, soil disturbance, wear and corrosion of subsoiler with S-T-SK-2# biomimetic structures (S means subsoiler; T means tine; SK means shank; 2#, h/s=0.57, h=5 mm and α=45°.) and self-healing coating under two seasons, two locations with different soil properties (black loam and clay soil) and subsoiling speeds (2 km/h and 3.6 km/h) were investigated. The soil moisture content and compactness affected the tillage resistance and wear-corrosion. The tillage resistance and degree of corrosion on all subsoilers were much larger in clay soil than that in black loam soil. Compared with S-T-SK-2#, the tillage reduction rate of C-S-T-SK-2# (S-T-SK-2# with self-healing coating) was up to 14.32% in clay soil under the speed of 2 km/h. The significance tests of regression equation results showed that subsoiler type and soil properties had a significant impact on soil disturbance coefficient, swelling of total soil layer, bulkiness of the plough pan. It is of a guiding significance for the analysis of soil disturbance. Synergism mechanism of subsoiler coupling with biomimetic structures and self-healing coating was analyzed in following. It depicted the guiding effect of biomimetic structure and the shield function of self-healing coating, resulting in anticorrosion and wear resistance of subsoiler.

Keywords: soil types, tillage resistance, wear-corrosion, soil disturbance, self-healing
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1 Introduction

Subsoiling has been widely used all over the world as an important operation method of no-tillage farming. It will break up density soil layers, increase water infiltration, and produce an appropriate soil disturbance to enhance root growth and development, which increases crop yield[1]. However, as a result of the increasingly severe soil compaction and the thickening of the plough pan, the friction between agricultural engagement and soil will lead to drag and energy consumption increasing and the wear has become more serious. Subsoiling depth, soil properties, and subsoiler type will affect the tillage resistance, soil disturbance and wear morphology of subsoiler. The subsoiling depth is determined by the root limiting layer and soil compaction layer. Soil moisture content, compactness, and soil type have a significant effect on the tillage resistance[2].

At present, the drag reduction methods in subsoiling mainly include electroosmotic drag reduction, magnetization drag reduction, spatial structure optimization of parts, vibration drag reduction and biomimetic drag reduction. In which, biomimetic science as a promising scientific field provides inspiration for engineering design and makes up for the defects of traditional methods[3]. Over a long period of evolution, creatures in nature had excellent drag reduction structures and functions. The biomimetic theory and technology of agricultural machinery, aimed at the technology problems which affected the level of agricultural mechanization and grain yield, such as high resistance, high energy consumption and low efficiency, applied biological desorption drag reduction and biological tribology principle to the design of agricultural machinery[4,5]. In previous work, the biomimetic triangular prism (BTP) and biomimetic partial circular column (BPCC) structures extracted from the shark scale were applied to the subsoiler. The simulation results showed that the bionic

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Biographies: Yueming Wang, PhD, research interest: agricultural engineering, self-healing material. Email: 468119083@qq.com; **Chenjie Lu**, MS, research interest: agricultural engineering. Email: 1278257089@qq.com; **Jing Chen**, Senior Agronomist, research interest: anti-wear-corrosion. Email: 169333333@qq.com; **Chenhuan Cui**, PhD, Professor, research interest: anti-wear-corrosion. Email: cuich@zucc.edu.cn; **Yijie Pan**, MS, research interest: anti-corrosion material. Email: yijie.pan@fusteel.com; **Wilhelm Pfleging**, PhD, Professor, research interest: drag reduction. Email: wilhelm.pfleging@kit.edu
***Corresponding author: Jiyu Sun**, PhD, Professor, research interest: agricultural engineering, anti-wear-corrosion, Mailing address: Key Laboratory of Bionic Engineering (Ministry of Education, China), Jilin University, Changchun 130022, China, Tel: +86-13504422192, Email: sjy@jlu.edu.cn

subsoilers with triangular prism elements had an obvious tillage resistance characteristic. The field experiments results showed that the biomimetic subsoiler with low tillage resistance would be helpful to increase the root absorption capacity of water and nutrients, which promote crop growth and increase the crop yield[6].

Combined with metal corrosion, it has an important impact on the economy benefit, safety performance, and resource protection[7]. It is estimated that the amount of metal scrapped as a result of corrosion in the world is equivalent to 1/4-1/3 of the annual production of metals, and the annual loss caused by corrosion in developed country accounts for 3%-4% of gross national product with an increasing trend year by year. During subsoiling process, subsoiler is destroyed by the chemical and electrochemical actions of the surrounding soil medium, namely, soil corrosion[8-10]. It would reduce the efficiency and life of the working parts which reduces the economic benefits of conservation tillage. Compared with other general medium, many characteristics of the soil, such as, diversity, inhomogeneity, multiphase, time seasonality, and regionality, makes the different corrosiveness[11]. The main types of corrosion are localized, pitting, crevice, and uniform corrosion. The physical properties, structure, porosity, and water content of the soil will affect the corrosion type and strength.

At present, there are various measures to protect metals against corrosion, such as, cathodic protection, anodic passivation, active corrosion inhibition, and organic coating[12]. In which, the organic coatings are simple and effective measures to offer an effective physical barrier and hinder the access of violent materials to the substrate, which improve corrosion performance of tillage tools to extend the service life of steel components[13]. However, microcracks would occur under the interaction between the coating and other objects. The defects will be extended along the microcrack. Therefore, active self-healing of defects in coating is more important for a long-term protection effect. Self-healing materials was a rapidly development area, which was of great significance for repairing microcracks and mechanical damage of materials[14,15]. Based on the previous work, a coating synthesized with polyester resin powder and nano-sized self-healing capsules containing tung oil has a significant effect on the corrosion resistance of the metals. When microenvironment changes, the self-healing agent is released to the damaged site by capillary siphoning to solidify and fill the microcracks to enhance the coating performance[16].

In summary, tillage reduction, wear resistance and anti-corrosion have attracted wide attention. The field experiment is an important measure to evaluate drag reduction performance and tillage quality of subsoiler under actual complex working conditions which could not be met in simulation and laboratory experiment. In this paper, based on the previous research on biomimetic structures and self-healing materials, a construction mechanism of coupled bionic synergistic surface is proposed to apply to the design of key components of subsoiler. Tillage resistance, soil disturbance, wear and corrosion of subsoiler with self-healing coating under different soil properties and subsoiling speeds are investigated. Then, comparisons of different soil properties on tillage resistance and corrosion are analyzed. And the synergism mechanism is proposed.

2 Materials and method

2.1 Experimental site

In this paper, the performance and operation quality of subsoiler under different soil properties are investigated. The first field experiments are carried out in the crop growth season in 22, June with about 28℃ at the maize crop experiment farmland of Jilin Agriculture University, Changchun, Jilin Province, as shown in Figure 1a. The soil type is black loam soil. The second field experiments are carried out in May 25 with about 28℃ during the crop farming season in Experimental farmland of Dieshang Experimental Station, Institute of Grain, Oil and crops, Academy of Agriculture and Forestry, Gaocheng County, Shijiazhuang City, Hebei Province, as shown in Figure 1b. The soil type is clay soil. The loading time for the soil could be shortened by increasing the subsoiling speed, which could reduce the compaction of the soil. However, excessive speed would increase the soil disturbance. At present, the domestic subsoiling speed was 2-7 km/h. To ensure the smooth process of data acquisition and avoid the distortion of the data signal due to excessive speed, as well as the same parameters compared with the previous experiment, the operation speeds during the field experiment were set to 2 km/h and 3.6 km/h. The subsoiling depth is 40 cm.


a.


b.

a. Maize Crop Experiment Farmland, Jilin Agricultural University, Changchun, Jilin b. Experimental farmland of Dieshang Experimental Station, Institute of Grain, Oil and Crops, Academy of Agriculture and Forestry, Gaocheng, Hebei Province

Figure 1 Field experiment site

2.2 Soil physical properties

Soil compactness (cone index) and moisture content influence the tillage resistance. In the previous work, soil compactness and moisture content of black loam soil (Maize Crop Experiment Farmland, Jilin Agricultural University, Changchun, Jilin Province) have been measured. In this paper, soil compactness and moisture content of clay soil (Experimental farmland of Dieshang Experimental Station, Institute of Grain, Oil and crops, Academy of Agriculture and Forestry, Gaocheng County, Hebei Province) are measured with soil compactness measuring instrument (SC-900 handheld digital penetrometer with depth accuracy of 1.25 cm and compactness accuracy of ±103 kPa) and weighing method, respectively. The comparisons with that of black loam soil are shown in Figure 2.

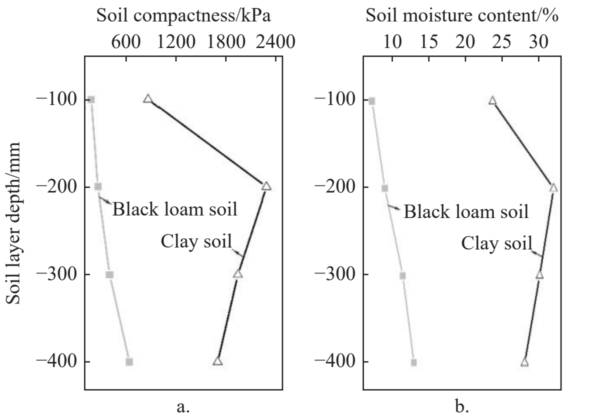


Figure 2 Soil compactness and moisture content in different tillage layers of black loam and clay soil

2.3 Subsoiler type

Based on the previous simulation results, ordinary subsoiler (O-S) and 9 biomimetic subsoilers are fabricated to carry out the field experiments. The field test results of tillage resistance and wear morphology of O-S and biomimetic structural subsoilers show that S-T-SK-2# (S means subsoiler; T means tine; SK means shank; 2#, h/s=0.57, h=5 mm and α=45°.) has excellent comprehensive properties in black loam soil. The coating synthesized with polyester resin powder and nano-sized self-healing capsules containing tung oil is coupled to O-S and S-T-SK-2# using electrostatic spraying, going through the processes of sand blasting, washing, blowing, spraying and solidifying, marking C-O-S and C-S-T-SK-2#, respectively, to carry out the field experiments in the black loam soil and clay soil, as shown in Figure 3.

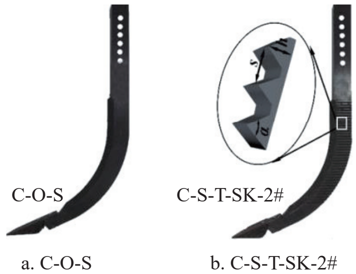


Figure 3 Subsoilers after coating

2.4 Experimental process

The subsoiler, sensors, and data collector are connected to the tractor in the correct way. Type B1-S sensors (China Academy of Aerospace Aerodynamics) were selected in data collector with a three-point suspension mounting. The sampling frequency was set as 5 Hz, which meant taking a data point every 0.2 s. The equipment is detected if working properly. The tractor first enters the 10 m debugging section, and the subsoiler is reduced to the test depth of 40 cm through the hydraulic system and maintained. The working speeds of the tractor are set of 2 km/h and 3.6 km/h, respectively. When the tractor enters the 40 m test section, the data are collected and stored. In this paper, the tillage resistance, soil disturbance, wear and corrosion of subsoiler with S-T-SK-2# biomimetic structure and self-healing coating under different soil types and subsoiling speeds are investigated.

3 Results

3.1 Tillage resistance under different soil properties

C-O-S and C-S-T-SK-2# are carried out the field experiments in black loam soil and clay soil. The tillage resistances of C-O-S and C-S-T-SK-2# compared with O-S and S-T-SK-2# in different soil properties under the speeds of 2 km/h and 3.6 km/h, respectively, are shown in Figure 4.

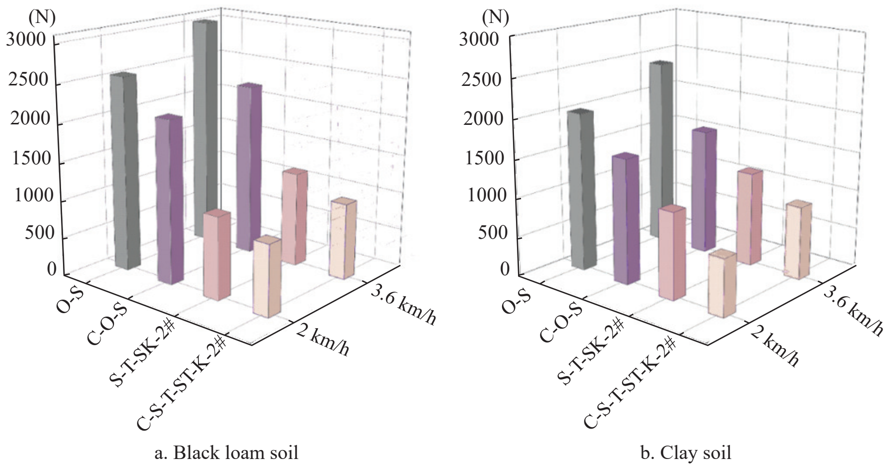


Figure 4 Tillage resistance of C-O-S and C-S-T-SK-2# compared with O-S and S-T-SK-2# in different soil properties under the speeds of 2 km/h and 3.6 km/h

The results show that compared with O-S and S-T-SK-2#, the tillage reduction rates of C-O-S and C-S-T-SK-2# are up to 13.26% and 15.38% in black loam soil, 11.09% and 14.32% in clay soil, under the speed of 2 km/h, respectively, and 14.25% and 16.34% in black loam soil, and 12.45% and 15.30% in clay soil, under the speed of 3.6 km/h, respectively. It indicated that self-healing coating has the effect of reducing tillage resistance. This is because the properties of surface material affect the wettability of soil solution, the formation of water film, and the strength of positive electric field. Due to the structure of Si-O tetrahedron and Al-O octahedron in the soil, the silicon and aluminum in the center of the crystal are replaced by low-valence elements, and some of the silicon dioxide in the crystal is hydrolyzed to silicic acid. In addition to the humus carboxylic acid, the surface of soil particle is with negative charge. Soil electric field is an important controlling factor to the mesoscopic scale effect, which controls and affects the stability of soil aggregate. It makes the destruction of soil aggregate with special ion effect. Therefore, mesoscopic scale soil electric will affect the macroscopic soil water movement, and make the water movement with the special ion effect of mesoscopic scale[17]. High molecular polymer self-healing coating can hinder the development of positive electric field to reduce the adhesion of soil. If the adhesion of the soil to the tillage parts surface is greater than the cohesion between the soils, a soil mass will be formed by stacking along the slip surface of tillage parts, which makes the friction resistance between the soil and soil replace that of between the soil and tillage parts[18]. It is equivalent to changing the shape and material of parts. The soil in the soil mass is replaced at any time with the moving of the subsoiler, but with the soil mass and subsoiler as a whole, when the friction coefficient between soil and soil is larger than that between soil and subsoiler, the tillage resistance will increase[19]. In addition, the geometry shape and dimension of the subsoiler as well as the movement direction of the cultivation soil are changed after adhesion between the soil and subsoiler, which affect the tillage quantity. Therefore, the subsoiler with self-healing coating has the positive effect of drag reduction.

The tillage resistance is increased with the increasing of the speed. This is due to the larger shear force produced by the high speed at the clay soil increases the friction between the soil and subsoiler, and the amount of soil thrown, which leads to the larger tillage resistance.

3.2 Corrosion morphology of subsoiler under different soil properties

After 30 d of subsoiling working in the lab with the temperature of 21℃-23℃ and the relative humidity of 34%-36%, the subsoiler surface morphology of O-S and C-S-T-SK-2# under different soil properties are shown in Figure 5. It shows that the abrasion on surface of O-S is severe and occurs a layering phenomenon. However, C-S-T-SK-2# with self-healing coating still has excellent surface topography after subsoiling. The degree of corrosion on the surface under clay soil is greater than that under black loam soil.

a. Black loam soil b. Clay soil

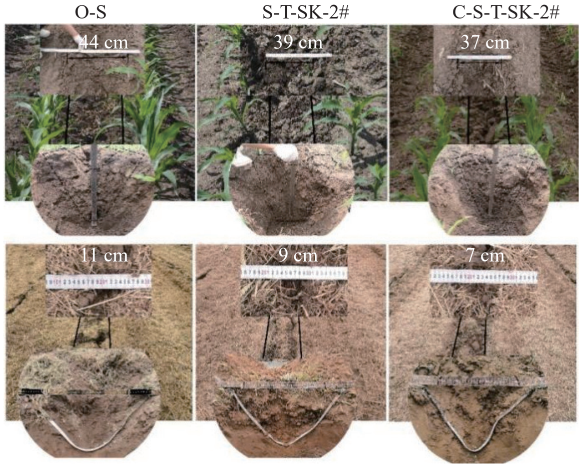
Figure 5 Surface morphology of O-S and C-S-T-SK-2# after subsoiling in black loam soil and clay soil

3.3 Soil disturbance under different soil properties

The soil disturbance morphologies of O-S, S-T-SK-2#, and C-S-T-SK-2# under the subsoiling speed of 2 km/h after subsoiling in black loam soil and clay soil are shown in Figure 6.

They produce a similar upper width and narrower plough bottom soil disturbance structure. Compared with the soil disturbance surface morphologies in different soil properties, the groove width after subsoiling with O-S, S-T-SK-2#, and C-S-T-SK-2# are 44 cm, 39 cm, 37 cm in black loam soil, and 11 cm, 9 cm, 7 cm in clay soil, respectively.

The soil disturbance profile is imported into AutoCAD software for curve fitting to calculate the soil disturbance coefficient (x) (the elevated soil area divided by the cross-sectional area from the surface to the theoretical subsoiling bottom before subsoiling (A_c)), swelling of total soil layer (y) (the disturbed soil area of total soil layer divided by A_c), and bulkiness of the plough pan (y') (the disturbed soil area of plough pan divided by A_c) in black loam soil and clay soil, as listed in Table 1.



a. Black loam soil b. Clay soil

Note: Solid black line meant groove mark after subsoiling; broken black line meant cross soil disturbance profile.

Figure 6 Soil disturbance surface and cross morphologies of O-S, S-T-SK-2# and C-S-T-SK-2# under the speed of 2 km/h in the field experiment of black loam soil and clay soil

Table 1 Soil disturbance coefficient (x), swelling of total soil layer (y), and bulkiness of the plough pan (y') of O-S, S-T-SK-2# and C-S-T-SK-2# in black loam soil and clay soil

Subsoiler	in black loam soil			in clay soil		
	x/%	y/%	y'/%	x/%	y/%	y'/%
O-S	25.86	45.81	20.02	20.49	36.80	14.19
S-T-SK-2#	19.27	34.45	31.17	13.17	29.92	18.56
C-S-T-SK-2#	17.49	32.76	33.72	12.05	26.22	20.19

The groove width of subsoiler in clay soil is much smaller than that in black loam soil, and the soil disturbance coefficient and the bulkiness are also smaller than that of black loam soil. This is because that the high soil moisture content in clay soil leads to large soil cohesion. During the shearing process, it occurs plastic flow instead of brittle fracture, resulting in small groove width and high soil backfill rate.

The significance tests of regression equation of between subsoiler, soil and x, y, y' are listed in Table 2. The goodness of equation fitting R^2 of subsoiler and soil are 0.920 and 0.917, respectively, which means the good fitting effect. The results show that subsoiler and soil have a significant impact on y, x, y'. The subsoiler has the greatest impact on x, followed by y and y'. The soil has the greatest impact on y', followed by x and y. At the same time, subsoiler has a greater impact on x and y, and smaller impact on y' than soil. It is of guiding significance for the analysis of soil disturbance.

Table 2 The significance tests of regression equation of subsoiler and soil

Subsoiler	F	Sig.	R^2	Soil	F	Sig.	R^2
x	20.65	0.020		x	13.93	0.034	
y	22.28	0.018	0.920	y	10.73	0.047	0.917
y'	10.25	0.049		y'	17.99	0.024	

4 Discussion

4.1 Effect of soil properties on tillage resistance

According to Figure 4, compared with the tillage resistance in the different soil properties, it is much larger in clay soil than that in black loam soil. Soil is a kind of semi-infinite continuous loose medium. At the same part and speed, different soil initial state leads to different cohesion, friction, and adhesion, resulting in different forms of soil failure[20]. Stafford showed that the soil behavior changed from compacted state (dry) to loose state (wet). The different increase rate of effective spherical stress and deflection stress produces different soil failure forms, either brittle fracture or plastic flow. In the low moisture content, the soil as a rigid brittle material occurs brittle fracture. However, in the high moisture content, the whole soil produces plastic flow, without main failure surface. In the process of relative movement between the soil and part, the friction mechanism is different from that between rigid bodies[21]. The adhesion theory should be considered. The friction resistance F between the soil and part is related to load, but also to the contact area and normal adhesion, as shown in Equation (1).

$$F = \mu'(N + CA) \tag{1}$$

where, F is friction resistance, N; μ' is proportional coefficient of tangential resistance to normal force; N is normal load, N; C is normal adhesion force per unit area, N/m^2; A is contact area, m^2.

For a given material surface, adhesion occurs when the soil moisture content exceeds a certain value. When the soil is contact with part, the particle group tends to interface shape of the part in contact with it under pressure, and the water film is formed between the soil and part interface. After that, if the soil is separated from the surface of the part, namely, the boundary layer will be divided into two surfaces, the surface suction between the soil and part needs to be overcome[22]. The adhesion between the soil and part is composed of electrostatic suction, intermolecular van der Waals force, capillary force, liquid viscosity resistance, unbalance force such as osmotic pressure difference caused by concentration gradient of solution, and solute chemical bonding resistance[23]. The separation surface appears in the weakest liquid layer, and the large distance between the liquid layer and the part causes the weak electrostatic suction and intermolecular van der Waals force. In the subsoiling process, the soil does not have fixed contact with the subsoiler for a long time, so the solute chemical bonding resistance can also be ignored. The thickness, continuity, and the surface tension of water have an important influence on adhesion. Soil moisture content, metal surface roughness and hydrophilicity affect the integrity of water film.

In the low soil moisture content, the continuous water film is destroyed, and the capillary phenomenon occurs between the soil particle and the subsoiler surface. At this time, the adhesion force is mainly affected by capillary force[24]. With the increase of soil moisture content, the water film formed between the soil and subsoiler is relatively complete. The effect of the force field of soil matrix and subsoiler solid surface on water molecules in the water film is weak. Its structure and energy state are the same as those of free aqueous solution. At this time, the adhesion force is affected by the unbalance force such as liquid viscosity resistance and osmotic pressure difference caused by solution concentration gradient[25]. Therefore, for a given material surface, with the increasing of soil moisture content, the gradually complete water film increases the adhesion of the soil to the subsoiler, which results in the larger friction resistance. However, when the moisture content increases to the critical state, the meniscus disappears, and the viscous resistance leads to the decrease of the adhesion force.

With the increase of soil compactness, the particle density in the soil and the interface increases resulting in the smaller pores, which will increase the water film contact rate per unit area (that is, C and A will be increased according to Equation (1)), resulting in high adhesion. When the compactness reaches a certain limit, the particle will be contact with the surface directly, and the lubricating water film will be squeezed out, which will increase the friction coefficient and friction resistance (that is, μ' will be increased according to Equation (1)), as shown in Figure 7.

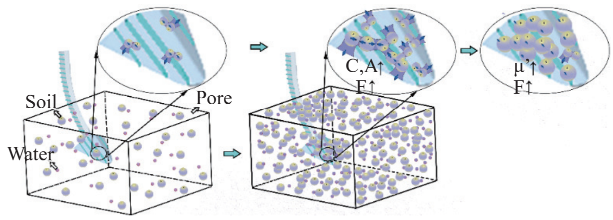


Figure 7 Effect of soil compactness and moisture content on tillage resistance

The soil compactness and moisture content of black loam soil (the maize crop experiment farmland of Jilin agriculture university, Changchun, Jilin Province) are lower than that of clay soil (experimental farmland of Dieshang Experimental Station, Institute of Grain, Oil and Crops, Academy of Agriculture and Forestry, Gaocheng County, Hebei Province). Therefore, according to the above theoretical analysis, it is shown that the friction and adhesion in clay soil are greater than those in black loam soil, thus increasing the subsoiling resistance, which is consistent with the results of field experiments.

4.2 Effect of soil properties on corrosion

The interaction form and effect between the soil parts and the soil are extremely complex, which makes its comprehensive performance in the tribology system closely relates to the contact form, environment, and operation condition. It is the result of the comprehensive action of mechanical, physical, and chemical. The soil mainly produces electrochemical corrosion to the metal. The corrosion current determinates the speed of corrosion, which is proportional to the electromotive force of the corroded battery and inversely proportional to the total electrical resistance of the loop, as shown in Equation (2).

$$I = \frac{E_c - E_a}{R_S + R_c + R_a} \tag{2}$$

where, I is corrosion current, A; E_c is cathode potential, V; E_a is anode potential, V; R_s is soil electrical resistance, Ω; R_c is cathodic polarization resistance; R_a is anodic polarization resistance, Ω.

Therefore, the corrosion rate is not only determinate by the nature properties of the metal itself, but also physical and chemical properties of the soil, such as moisture content, porosity, fertilizers, pesticides, erosion, and other acid medium in the soil, the proportion, hardness, sharpness, and shape of the soil particle.

The moisture in the soil is one of the most important factors to cause corrosion. Firstly, soil becomes an electrolyte in the presence of water, which is a prerequisite for electrochemical corrosion. Secondly, the different moisture content makes the different physical and chemical properties of the soil, which affects in turn its corrosion behavior. The soil moisture content can change the ion activity and electrical resistance in the soil, resulting in different air content, oxygen content, and permeability in the soil[26]. These factors have an important effect on the metal electrode potential and cathodic polarization. Normally, the soil corrosivity increases with the increasing of soil moisture content within a certain range. The corrosion rate reaches the maximum until the critical humidity, and then decreases with the increasing of moisture content. According to Figure 6, the corrosion patterns of subsoiler in black loam soil and clay soil are local corrosion and uniform corrosion, respectively. This is because the different moisture content has different influence on corrosion morphology of metal. When the soil moisture content is within a certain range, continuous liquid film with uniform thickness gradually forms between the interface of the metal and soil with the increasing of soil moisture content. Therefore, the electrochemical difference between the two gradually decreases, resulting in the corrosion from local to the uniform on the metal surface. In addition, oxygen content and salt content will change with the increasing of moisture content, which promotes the formation of oxygen concentration and salt concentration cell, increasing its corrosivity.

The larger soil porosity is beneficial to oxygen permeation and water conservation. Oxygen and water are the contribution factors to corrosion. Therefore, the larger soil porosity will accelerate the soil corrosion process. At the same time, however, the soil with good permeability is also prone to produce corrosion products with protective ability, thus inhibiting the anodic dissolution of metals to slow down the corrosion rate[27]. As a trend, the large firmness and small porosity lead to poor permeability, resulting in severe metal corrosion.

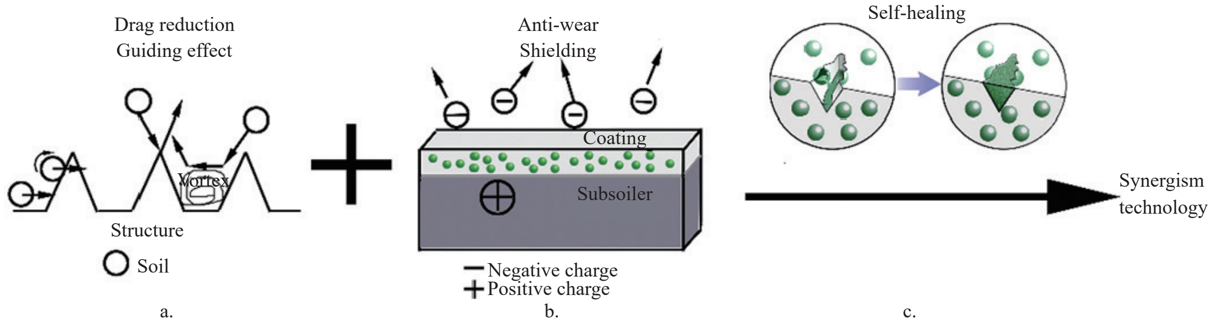
It can be seen from Figure2 that the water content and firmness of clay soil are significantly higher than that of black loam soil. Therefore, the clay soil has a large porosity and poor permeability. Subsoiler surface is more corrosive in clay soil than in black loam soil, which is consistent with the field experiment results.

4.3 Synergism mechanism analysis

The surface of O-S without self-healing coating occurs crack, corrosion pits and exfoliation. This is mainly due to the plough fatigue of the soil particles in relation to the surface of the subsoiler, resulting in serious plastic deformation of material. When the plastic deformation reaches the limit strength, the material is destroyed and finally exfoliated from the surface to form a micro-ploughing groove. Combined with soil adhesion, the soil is an extremely complex heterogeneous system consisting of soil particles, water, gas and organic compounds, which is easy to form oxygen concentration cell corrosion with a hazard to the subsoiler[28]. The soil corrosion is an electrochemical process. Anode and cathode connect through the body of the corroding metal itself, which play a mixed electrode[29]. The coupled anodic and cathodic reactions take place on the metal surface. The necessary oxidizing agent used to consume electrons released from the corroding metal is provided for corrosion due to the exposure in atmosphere environment, and ploughing groove on the metal surface is favorable to the formation of water film, which accelerates the electrochemical corrosion of the metal surface, even in the low relative humidity environment[30]. First, the metal surface is gray and gradually changes color, and then rusty, destroying the appearance of the surface. There may be no any major problems in a short period of time, but the danger is latent. When corrosion reaches a certain degree, it will cause obvious damage and affect the subsoiling working.

In addition to the adhesion and friction effects, the surface wear, such as abrasive wear, fatigue wear or corrosion wear, is also caused by the contact and slippage between the interface of the subsoiler and soil, which produces adverse consequences increasing the tillage resistance. However, the surfaces of C-S-T-SK-2# with self-healing coating are excellent. The interaction between the subsoiler and soil produces the micro crack. When the crack propagates along the coating to penetrate the microcapsule, self-healing agent will be released, which forms a cross-linking network rapidly to prevent the crack growth. Therefore, the self-healing coating restrains of the formation of ploughing groove of the metal surface to reduce the adhesion of water film. In addition, the self-healing coating can hinder the adhesion of the soil, which will reduce the soil corrosion. Once the corrosion occurs, the self-healing agent will be released to bind and fill in the microcracks, which will repair the internal damage of the material. At the same time, it has excellent permeability shielding performance to reduce the corrosion rate to protect the metal. Therefore, self-healing coating is of great significance to the anticorrosion and wear resistance of subsoiler.

In summary, the synergism mechanism diagram of subsoiler coupling with biomimetic structures and self-healing coating is shown in Figure 8. Firstly, the biomimetic structure produces guiding effect to the soil to reduce the contacted area, and destroys the sealing to reduce the adhesion, which resulted in the friction force reduction. Then, the self-healing coating shields the soil aggregate to reduce the adhesion of soil, which has the positive effect of drag reduction. Once the crack, plough fatigue or other corrosion occurs, the self-healing coating will automatically repair to reduce the corrosion rate to protect the metal, which is of great significance to the anticorrosion and wear resistance of subsoiler.



a. Guiding effect produced by biomimetic structure b. Destruction of soil aggregate produced by self-healing coating c. Self-healing property

Figure 8 Tillage resistance reduction of mechanism of self-healing coating anticorrosion and wear resistance

5 Conclusions

The tillage resistance, soil disturbance, wear and corrosion of subsoiler with S-T-SK-2# biomimetic structure and self-healing coating under different soil properties (black loam and clay soil) and subsoiling speeds (2 km/h and 3.6 km/h) are investigated. The field experiments results show that self-healing coating has the positive effect of reducing tillage resistance and anti-corrosion. The tillage resistance and the degree of corrosion on the surface in clay soil are much larger than that in black loam soil. Compared with O-S and S-T-SK-2#, the tillage reduction rates of C-O-S and C-S-T-SK-2# are up to 15.38% and 13.26% in black loam soil, 11.09% and 14.32% in clay soil, under the speed of 2 km/h, respectively, and 14.25% and 16.34% in black loam soil, and 12.45% and 13.30% in clay soil, under the speed of 3.6 km/h, respectively. The groove width of subsoiler, soil disturbance coefficient, and the bulkiness in clay soil are much smaller than that in black loam soil. Subsoiler type and soil properties have a significant impact on soil disturbance coefficient, swelling of total soil layer, bulkiness of the plough pan. Subsoiler type has the greatest impact on soil disturbance coefficient, followed by swelling of total soil layer, and bulkiness of the plough pan than soil. The soil property has the greatest impact on bulkiness of the plough pan, followed by soil disturbance coefficient and swelling of total soil layer. At the same time, subsoiler has a greater impact on soil disturbance coefficient and swelling of total soil layer, and smaller impact on bulkiness of the plough pan than soil. It is of guiding significance for the analysis of soil disturbance.

The synergism mechanism diagram of subsoiler coupling with biomimetic structures and self-healing coating is analyzed. The self-healing coating shields the soil aggregate to reduce the adhesion of soil. Once the crack, plough fatigue or other corrosion occurs, the self-healing coating will automatically repair to reduce the corrosion rate to protect the metal, which is of great significance to the anticorrosion and wear resistance of subsoiler. However, there are still many challenges to the fully realize the potential of self-healing coating in corrosion and abrasion resistance in subsoiler. Next-generation application of self-healing coating will highlight the adhesion between the coating and substrate and extend protection time with accelerated corrosion test.

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