

农机触土部件减粘脱附研究现状与展望

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摘要: 农机触土部件的土壤粘附问题是制约农业机械作业质量、生产效率与服役寿命的关键瓶颈,随着农业装备向大型化、复式化、高速化发展,对其减粘脱附性能的要求愈发苛刻。本文系统分析了土壤粘附的形成机理及其影响因素,重点综述了振动、气动、加热、结构优化、表面技术及仿生设计等减粘脱附技术在旋耕刀、开沟器、深松铲、挖掘铲、镇压轮、移栽器等农机触土部件相关研究及应用的国内外现状,剖析了当前研究存在的不足,并从粘附失效理论构建、高性能涂层材料研发、仿生结构创新设计等方面展望了未来研究方向,以期能为农机触土部件减粘脱附技术的创新突破与工程应用提供理论参考和技术借鉴。

关键词: 农业机械; 触土部件; 减粘脱附; 表面处理

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Research Status and Prospects of Reducing Adhesion and Facilitating Detachment on Ground-contact Components of Agricultural Machinery

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Abstract: Agricultural machinery serves as the backbone of modern agricultural production, as its operational performance and reliability directly impact national food security. As the mechanization of agriculture and the upgrading of agricultural equipment continue to advance, there is an increasing demand for enhanced performance in soil-engaging component, such as plowshares, tillage tools, and trenchers. Soil adhesion during operation leads to increased resistance and energy consumption, resulting in irregular furrowing, inadequate soil breakup, and uneven compaction, ultimately diminishing operational quality and efficiency. Thus, addressing soil adhesion in soil-engaging component is essential for maximizing the performance potential of agricultural equipment. The mechanisms of soil adhesion formation and the factors influencing it were systematically analyzed. A comprehensive review of the current state of research, both domestically and internationally, on technologies for reducing adhesion and facilitating detachment in agricultural machinery was provided. These included vibration, pneumatic methods, heating techniques, structural optimization, surface treatments, and biomimetic designs. Despite significant advancements in research aimed at reducing soil adhesion on agricultural machinery, current technologies still had considerable room for improvement to meet the high-quality development demands of agricultural equipment in China. While vibration, pneumatic, thermal, and structural adhesion reduction techniques showed effectiveness, they often require additional power sources or auxiliary systems, complicating machinery design and increasing energy consumption. Furthermore, many of these techniques were optimized for specific soil conditions, lacking comprehensive studies on their adaptability across diverse soil types and moisture levels. Surface engineering technologies, while capable of producing coatings with excellent initial adhesion reduction properties, often suffered from performance degradation due to wear and mechanical impacts during actual operations. Existing research tended to focus too heavily on optimizing single properties of coatings, with insufficient attention to the synergistic enhancement of wear resistance and anti-adhesion capabilities. Additionally, biomimetic approaches,

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though promising, often lack universal design models that can adapt to various conditions, and they required further exploration of cost implications and complexity in manufacturing processes. The operational conditions for soil-engaging component were harsh, and understanding the complex mechanisms of soil adhesion was vital for enhancing their adhesion reduction and detachment performance. Future research should focus on dynamic, multi-field coupling studies of soil-component interfaces, the development of specialized low-energy adhesion reduction materials, and the transition from static to dynamic biomimetic designs, fostering innovative, cost-effective solutions that ensure high reliability.

Key words: agricultural machinery; ground-contact components; reducing adhesion and facilitating detachment; surface treatment

0 引言

农业装备作为现代农业生产的核心载体,其作业性能与可靠性直接关系到国家粮食安全。随着农业机械化和农业装备产业转型升级的持续深化,现代农业装备正逐步向大型化、复式化、高速化方向发展,这对农机触土部件的综合性能提出了更为严苛的要求。旋耕刀、开沟器、深松铲、挖掘铲、镇压轮、移栽器等农机触土部件在作业过程中普遍存在土壤粘附现象。土壤粘附不仅会使作业阻力增大、作业功耗增加,还会引发开沟不规整、碎土不彻底、镇压不均匀等问题,进而降低作业质量与效果,影响农业生产效率和经济效益^[1-2]。由此可见,触土部件的土壤粘附已成为制约农业装备性能充分发挥的关键瓶颈。

土壤粘附是涉及界面物理、化学与力学等多学科的复杂现象。自 20 世纪初毛细管理论与水膜理论提出以来,国内外学者围绕土壤-金属界面作用机制开展了系统深入的研究,为减粘脱附技术的研发奠定了坚实的理论基础^[3]。在此基础上,科研工作者采用破坏粘附界面^[4]、降低表面能^[5]、改善接触形貌^[6]、借鉴仿生学原理^[7]等手段,形成了振动、气动、加热、结构优化、表面技术及仿生设计等多条减粘脱附技术路径^[8-10]。然而,当前相关研究仍面临诸多挑战,如各类减粘技术难以在性能、成本与可靠性之间实现良好平衡,其作用机理与触土部件复杂动态服役行为之间的关系尚不明确等。为此,本文系统梳理农机触土部件土壤粘附的形成机理及其主要影响因素,综述国内外减粘脱附技术的研究进展,剖析当前存在的关键问题与不足,并对未来研究方向进行展望,以期为推动我国农机触土部件减粘脱附技术的创新与应用、提升农机装备整体作业效能与可靠性,提供理论参考与技术借鉴。

1 土壤粘附研究进展

土壤属分散体系,其固相由分散状态的土粒和

团聚体构成,液相为土壤溶液,气相为填充于土壤空隙中的空气。土壤含水率^[11]、土壤理化特性、触土部件材料性能及其表面粗糙度、土壤-部件接触面温度以及两者间相对滑动速度、土壤所受正压力等^[12-15]均对土壤与触土部件间的粘附和摩擦有影响。

土壤粘附主要发生在触土部件与土壤的接触界面,该粘附系统由土壤界面、水膜层和触土部件材料界面共同构成,其影响机制也取决于上述三大界面特性^[16]。黏粒含量高的土壤比砂粒含量高的土壤粘附力更强;粘附力的大小主要取决于接触界面的水膜张力,可近似表示为水分张力与水膜接触面积的乘积。因此随着土壤含水率升高,土壤与金属间的粘附力呈上升趋势,但当含水率达到土壤液限后,粘附力则开始下降^[17]。此外,材料表面特性对粘附作用也有较大影响。金属表面自由能影响金属与土壤间水分的接触状态,进而改变拉普拉斯(Laplace)压力的大小。当金属表面自由能较低、疏水性优良时,土壤的粘附作用较弱;反之,土壤的粘附作用较为显著^[18]。

针对土壤粘附机理,国内外学者提出了多种学说。20 世纪 20 年代初,HAINES^[19]提出了毛细管理论,该理论将土壤简化为球状颗粒堆积结构,并针对理想状态下土壤颗粒的松散堆积与紧密堆积两种情况,分别构建了球形粒子力学模型,获得了水分表面张力、土壤颗粒半径与粘附力的计算公式,揭示了水分表面张力与土壤颗粒间粘附力成正比、土壤颗粒半径与粘附力成反比的规律;20 世纪 50 年代,FOUNTAIN^[20]提出了水分张力理论(又称水膜理论,如图 1 所示),该理论至今仍是土壤粘附机理的核心理论之一。该理论指出,土壤与金属界面间的粘附力源于二者接触形成的界面水膜,其大小等于水分张力与水膜接触面积的乘积。其中,水分张力由土壤颗粒对水分的吸附力、Laplace 毛细压力及界面键合力共同组成,且会随土壤含水率的变化而变化。水分张力测定试验结果表明,当土壤含水率较低且土壤质地

较粗糙时,界面水分以不连续环状形式存在于接触点处,此时粘附力主要由局部水环张力主导(图 1a)。而当土壤含水率较高且土壤质地较细腻时,界面会形成与土壤内部水分相连通的连续水膜,此时粘附力则由整体水膜张力决定(图 1b)。

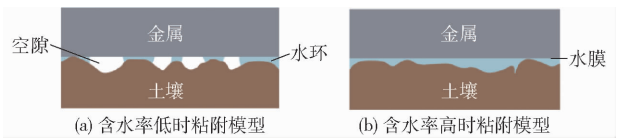


图 1 土壤-金属界面接触模型

Fig.1 Soil-metal interface contact models

20 世纪 80 年代,钱定华等^[21]建立了土壤对金属表面粘附的理论模型,并提出了五层界面理论。该理论认为,粘附模型(图 2)由金属层、金属表面-水界面层、水膜层、土壤表面-水界面层和土壤层 5 层结构组成,且土壤与金属表面的粘附力大小取决于 5 层结构中强度最弱的水膜层。粘附力的大小主要与水的表面张力、水膜面积与厚度等因素有关;张际先等^[22]从界面相互作用角度分析了土壤粘附机理,指出表面憎水性是土壤粘附的主要影响因素,并提出在高表面能材料表面制备憎水薄膜,可有效降低土壤粘附。

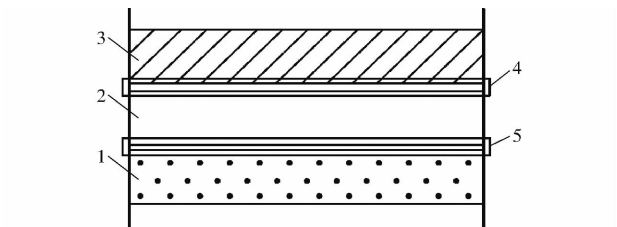


图 2 土壤粘附五层界面模型

Fig.2 Five-layer interface model of soil adhesion

1. 土壤层 2. 水膜层 3. 金属层 4. 金属表面-水界面层 5. 土壤表面-水界面层

2 触土部件减粘脱附技术研究现状

鉴于土壤粘附特性难以改变,当前针对触土部件的减粘脱附主要围绕结构优化、表面处理、仿生设计等措施开展。目前,触土部件常用的减粘脱附技术主要包括振动、气动、加热、结构优化、表面技术及仿生设计等。

2.1 振动减粘脱附

振动减粘脱附^[23]的基本原理是通过施加高频低幅的机械振动,破坏土壤与接触面之间的粘附联结,从而实现减粘脱附的效果。为探究超声振动切削土壤的减粘机制,QIAO 等^[24]提出了一种结合休止角试验与超声切削阻力试验的离散元参数标定方法,研究发现,高频激励的超声波振动破坏了土壤与刀具间的粘结键,改善了界面接触状态,实现减粘脱

附效果,为建立土壤-刀具高频振动相互作用的数值模型奠定了基础。王家胜等^[25]为揭示超声波高频振动条件下触土部件与土壤的相互作用力学特性,构建了一套超声波振动触土部件土槽试验系统(图 3),分析了高频振动对界面接触状态的影响。结果表明,高频振动使触土部件与土壤之间产生接触分离,并减少了二者间的接触时间,降低了土壤与部件界面间的黏滞力。

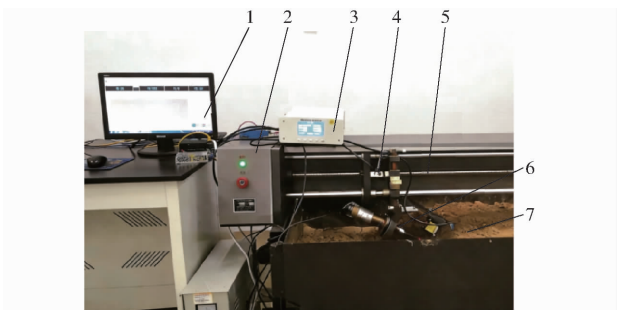


图 3 超声波振动触土部件土槽试验系统

Fig.3 Soil-tank test system of soil-engaging component with ultrasonic vibration

1. 计算机 2. 伺服电机 3. 超声波发生器 4. 力学传感器 5. 运动导轨 6. 超声波振动触土部件 7. 土槽

ZHOU 等^[26]设计了由变频振动电机驱动的仿蚁狮幼虫深松铲(图 4)。研究表明,高频振动与非光滑表面相结合可降低土壤内聚力、减小土壤内摩擦角、破坏接触部件与土壤接触面水膜层的连续性、改变土壤流动状态,从而减少界面层的粘附性。

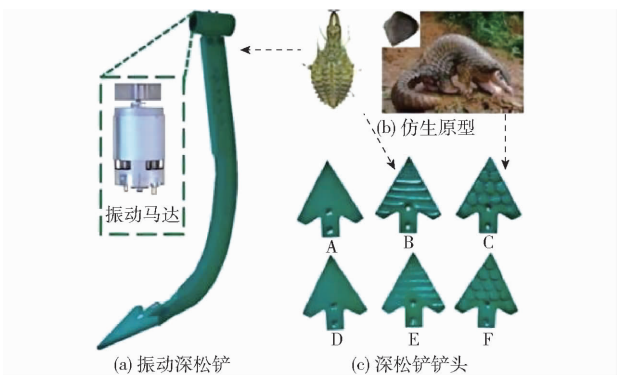


图 4 振动式电动仿生深松铲结构图

Fig.4 Design of vibrating electronic motor type bionic subsoilers

邱毅清^[27]基于自激振动与共振效应,在仿生推土板基底曲面叠加空间几何频谱,设计了双频自激振动式触土曲面结构。作业时,曲面上的几何频谱结构诱发土壤-部件系统产生自激振动,并利用共振效应引发的微幅高频振动使土壤-金属界面形成动态微间隙,不仅破坏了界面水膜的连续性和土壤的粘附层,显著降低了界面吸附力,还增强了土壤颗粒的流动性,削弱了堆积效应,从而实现良好的减粘脱

附效果。针对长江中下游水旱轮作区旋耕作业中土壤粘附严重的问题,刘国阳等^[28-30]将横挡阻隔防粘与振动脱附相结合,设计了一种振动横挡阻隔式防粘旋耕刀辊(激振装置见图 5),旋耕过程中,横挡形成封闭圆柱区域阻隔土壤直接接触刀轴,激振装置驱动横挡沿轴向往复运动,对夹塞土壤施加剪切作用,当剪切应力超过土壤抗剪强度时使土壤破碎脱落,横挡往复运动产生的振动加速度使附着在其表面的土壤颗粒所受惯性力超过界面粘附力,从而实现振动脱附。田间试验表明,该刀辊的减粘脱附性能较传统旋耕刀辊显著提高;通过构建土壤-金属界面粘附系统试验平台,系统分析了振幅、频率、时间等振动参数对脱附率的影响,为振动脱附装置的设计提供了理论依据;设计一种基于土壤表面粗糙度(SSR)动态反馈的智能旋耕机振动脱土系统。该系统通过采集耕后地表图像,基于分形维数与 SSR 参数的函数模型反演实时粗糙度,动态调控横挡振动装置实现土壤主动剥离,搭载智能振动脱附系统的旋耕机较传统旋耕机土壤粘附量降低约 59.5%,为实现稻田旋耕机的智能减粘和土壤剥离提供了有效的解决方案。

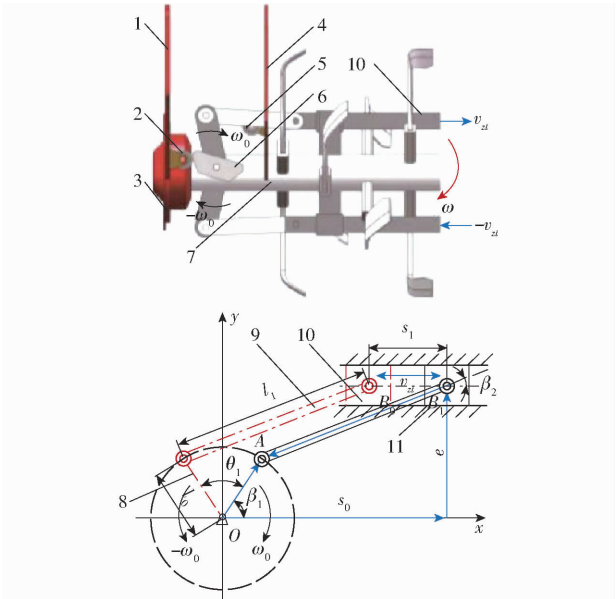


图 5 激振装置结构图

Fig.5 Schematic of vibration excitation device

1. 侧板 2. 升程滚子 3. 辊轴头 4. 挡泥板 5. 回程滚子
6. 旋转块 7. 刀轴 8. 摇杆 9. 连杆 10. 横挡 11. 滑槽

振动横挡阻隔式依靠横挡阻隔、剪切与振动的协同机制,减粘效果突出,其智能系统能动态适应土壤粗糙度变化,适用性强;双频自激振动能耗低,但部件与土壤发生共振的条件苛刻,结构设计制造难度大;超声波振动结构相对简单,但超声波振动在黏性土壤中高频衰减快,持续驱动发生器

能耗高。

2.2 气动减粘脱附

气动减粘脱附^[31]以压缩空气为能量介质,通过在物料与接触界面之间产生瞬时压力冲击,破坏其界面粘附作用,从而实现减粘脱附。LI 等^[32-34]设计了一种气动深松装置,构建了气动深松阻力模型(图 6),揭示了工作气压、深松深度与作业速度对牵引阻力的影响规律,并通过田间试验验证了气动深松的降阻效果。构建了工作气压、作业深度、前进速度、土壤容重及含水率等因素对深松阻力影响的 4 种预测模型,并量化了各参数对降阻的贡献度。采用主成分分析结合长短期记忆网络(LSTM)及双向 LSTM,开展气动深松土壤裂隙预测与扰动表面分析,结果表明 LSTM 在预测裂缝上表现优异,且气压是影响作业阻力与扰动表面的最主要因素,高压气体通过瞬时爆破扰动土壤,气体在土壤中扩散形成裂缝,破坏土壤颗粒间的粘结结构,降低了土壤的内聚力,同时减少了土壤与铲体表面的接触面积和正压力,从而降低了界面摩擦和粘附力。

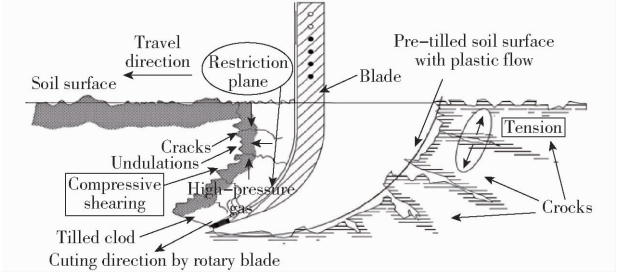


图 6 气动深松阻力模型

Fig.6 Schematic of pneumatic deep loosening resistance

李金光^[35]将深松铲土壤粘附机理分为铲面土核附着与铲侧土壤团聚体吸附。针对前者,耦合砂鱼鳗头部楔形结构与背部鳞片锯齿形貌,设计非光滑表面以抑制土核形成;针对后者,提出气体补偿式去真空解吸脱附方法,通过主动补气削弱吸附作用,设计了去真空式耦合仿生深松铲(图 7),降低了土壤粘附和耕作阻力。

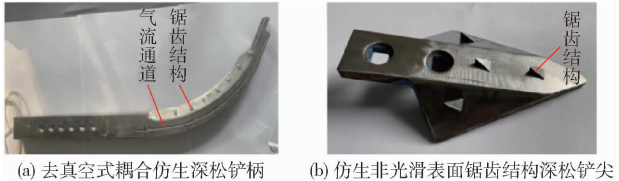


图 7 去真空式耦合仿生深松铲

Fig.7 De-vacuum coupling bionic subsoiler

气动式与去真空式均通过主动能量输入实现高效脱附,在黏重土壤中优势显著。但需配置空压机,能耗较高,相较于气动式,去真空式气泵可间歇工作,能耗相对可控。此外,去真空式仿生表面与气流

管路加工难度大。

2.3 加热减粘脱附

加热减粘脱附^[36]是指利用加热方式降低接触界面水膜的表面张力,以削弱物料与接触部件间的粘附力,从而达到减粘脱附目的。针对水稻收获机械抖动板表面湿黏物料粘附的问题,程超等^[36]提出了利用界面加热实现金属抖动板减粘脱附的方法,根据湿黏水稻物料与金属抖动板的粘附界面模型(试验装置见图8),揭示了水膜的毛细作用是粘附形成的重要因素,进而阐明界面加热使得水膜加速汽化破坏毛细桥梁以实现界面脱附的作用机理。



图8 振动加热脱附试验装置

Fig. 8 Vibration heating anti-adhesion test device

张敬宇^[37]设计了一种加热式法向拉拔与切向剪切试验装置,系统研究了预加荷载、加载速率、拉拔速率、含水率、加载时间及加热时间等因素对土-金属界面粘附特性的影响。研究表明,加热使金属-土界面水膜厚度减小、水膜连续性被破坏及表面张力降低,同时引发土体内水分在温度梯度作用下迁移,改变界面含水状态,从而削弱水膜的毛细吸附与黏滞作用;在切向剪切过程中,加热促使结合水析出形成润滑水膜,并降低水的黏滞系数,以降低界面粘附力。QIU等^[38]采用自研的界面温度粘附测试装置,控制界面温度与土壤含水率,测试了单位面积粘附力及粘附土量,从水分迁移和界面能量变化角度分析加热对粘附特性的影响。研究表明,界面温度升高导致界面影响范围内土体含水率变化,通过温度梯度引起的水分迁移使靠近界面的土壤水分减少,从而改变水膜厚度和分布。QIN等^[39]采用自主研发的外摩擦角测量装置,分析了不同热风温度与气压条件下土壤-机具界面摩擦角的变化规律,并结合土槽试验,系统研究了高压热风耦合作用对其影响机制,为触土部件加热减粘脱附提供了理论依据。

高压热风式减粘效果明显,但需配置空压机与加热设备,能耗高,结构复杂且气孔易堵塞;直接加热式结构简单,在中含水率粘性土壤中效果显著,但高含水率或长时间加热会导致粘附力增大。

2.4 结构减粘脱附

结构减粘脱附^[40]通过优化作业部件的几何构

型与结构参数,旨在削弱土壤与触土部件间的粘附作用,最终实现减粘脱附。针对黏重稻茬田油菜直播机旋耕及深施肥部件易堵塞、秸秆埋覆率低等问题,杜文斌等^[41]设计了一种可有效降低土壤粘附与入土阻力的组合式埋茬防堵装置(图9)。该装置在深施肥铲正前方安装埋茬弯刀,可实现碎土埋茬并刮削铲体以防止粘附;双刃旋耕刀采用滑切角较大的偏心圆弧刀口,可利于秸秆脱出避免堵塞;刀片人字型排布配合反向旋转,可促进土块流动,避免壅积。

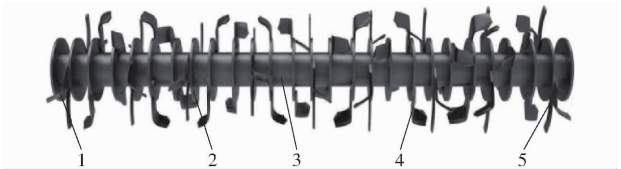


图9 组合式埋茬防堵装置

Fig. 9 Combined stubble burying anti-blocking device

1. 法兰盘 2. 旋耕刀盘 3. 筒状刀轴 4. 埋茬弯刀 5. 双刃旋耕刀

针对全自动移栽机在黏性土壤作业时鸭嘴土壤粘附严重的问题,段宇辉^[42]设计了一种鸭嘴刮土机构(图10)。该鸭嘴以粪金龟头部凸包为仿生原型,通过减小土壤与鸭嘴壁面的实际接触面积,破坏土壤的层状连续粘附状态,降低界面粘附力,其设计的刮土机构刮土率为92.5%。

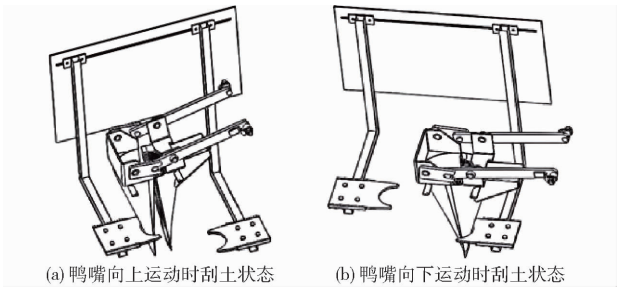


图10 鸭嘴运动时刮土状态

Fig. 10 Soil scraping state during duckbill movement

为抑制油菜免耕直播作业后粘土与秸秆回带现象,王立宗^[43]设计了一种由仿虎爪式刀齿、刮土板以及防缠板组成的辅助刮土装置(图11),实现了对粘附于辊体及刀齿表面的土壤的有效刮除。

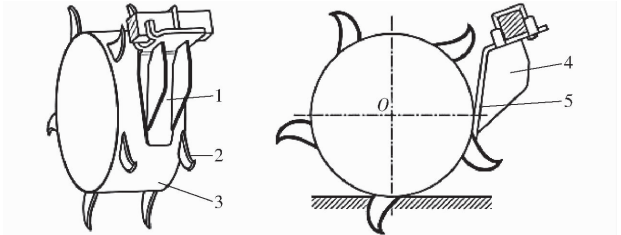


图11 刮土装置结构示意图

Fig. 11 Schematic of structure of soil-scraping device

1. 刮土装置 2. 掘茬刀齿 3. 辊体 4. 防缠板 5. 刮土板

针对丘陵山地黏重土壤环境下播种开沟器存在的粘土严重、开沟阻力大等问题,郝建军等^[9]基于非光滑表面减阻原理,通过在传统芯铧式开沟器犁体表面增设横向凸筋,有效降低了开沟器表面的土壤粘附和开沟阻力。土槽试验结果表明,在相同工作条件下,结构化改形开沟器较普通开沟器土壤减粘率为 16.33%,开沟阻力降低了 2.91%~4.45%。王磊等^[44]设计了一种集埋茬、防堵与深施肥于一体的复合作业装置,优化了深旋弯刀、浅旋弯刀、防堵直刀与菱形深施肥铲的结构参数,改进了刀片和深施肥铲排列方式,降低了深施肥铲表面的土壤粘附。FU 等^[45]采用响应面法对履带车辆的履刺高度、厚度及外扩角等结构参数进行优化,获得了履带粘土量最小时的最优履带结构参数组合,优化后的履刺土壤粘附量减少 4.63%。针对传统播种机限深轮土壤粘附严重、种沟成型质量差的问题,LI 等^[46]设计了一种带土壤保持槽与不规则腔体结构的弹性限深轮(图 12),不规则腔体结构显著增强了轮体的弹性,通过变形挤压土壤向内流动,有效减少了轮面与土壤的接触粘附,土槽试验结果表明,不规则腔体结构的限深轮相较传统限深轮土壤减粘率提升约 12.61%。



图 12 不规则腔体限深轮结构图

Fig. 12 Structure of the irregular cavity gauge wheel

LIU 等^[47]采用结构改型方法,引入莱姆尼斯卡曲线,构建了不同几何尺寸的非光滑凸包结构镇压轮(图 13),该几何构型通过控制凸包轮廓线的曲率变化,避免镇压轮与土壤之间形成真空积土区域,减小土壤与压轮表面的接触面积,破坏土壤粘附界面的形成条件,抑制粘附的形成。



图 13 莱姆尼斯卡曲线型镇压轮

Fig. 13 Lemniscate curve type press roller

针对稻茬田黏重土壤导致播种机作业时易发生泥土粘附的问题,LI 等^[48]研制了一种耐湿旋耕条播机,通过减小旋耕刀片宽度与优化刀轴转速提升离心自洁能力;以橡胶包覆星形式镇压轮替代传统镇

压轮,利用橡胶表面低粘附特性降低土壤粘附;机具后部加装不锈钢链条,利用其挠性不粘土的特点辅助覆土。从刀辊、镇压轮与覆土装置 3 个层面协同实现高湿黏重条件下的抗泥粘附作业。

仿生鸭嘴配合刮土机构减粘效果最佳,刮土机构相对简单,但刮土橡皮在作业过程中易磨损,需定期更换;增设横向凸筋改形开沟器减粘效果明显,工艺简单,但凸筋在作业过程中易磨损失效;相较于刮土和凸筋结构,组合式防堵装置、弹性不规则腔体及莱姆尼斯卡曲线结构较为复杂,加工成本高。

2.5 表面技术减粘脱附

表面技术减粘脱附通过制备低表面能涂层或构筑非光滑表面结构,调控触土部件表面材料特性或几何形貌。该技术通过减小界面接触面积、迫使界面水膜失稳失效、改变界面应力分布等,可有效降低土壤对触土部件的粘附倾向,最终实现减粘脱附的目标。

(1) 激光表面处理

WANG 等^[49]采用激光熔覆工艺在铲尖的前后表面制备了仿鲨鱼皮 V 形结构,研究表明,仿生 V 形结构改变了土壤-铲尖界面的相互作用状态,其研究不再仅依赖于减少与土壤接触面积,而是通过结构设计主动引导土壤与铲尖界面的流动行为,使得小颗粒土壤沿 V 形沟槽向耕作反方向疏导,减少了土壤在铲尖前端的堆积,实现了良好的减粘降阻效果。SUN 等^[50]运用三维扫描与选择性激光熔化技术,在开沟器表面精准构建了熊爪的多梯度曲面结构,其光滑与非连续特征有效减少了接触面积与粘附力,具有良好的减粘效果。ZHOU 等^[51]采用三维扫描和选择性激光熔化技术,构建了具有獾爪趾轮廓曲线特征的仿生深松铲,基于 EDEM 离散元法建立铲体-土壤-胡萝卜的耦合模型,研究表明,獾爪趾的曲线轮廓改变了土壤颗粒的运动轨迹,优化后铲翼结构的扰动范围增大,使得土壤团聚体破碎,破坏了土壤与铲面之间可能形成的连续粘附界面,使土壤更容易从铲面脱落。

(2) 表面钎涂

针对旋耕刀具在作业中面临耐磨、降阻与减粘多重性能需求,孙志鹏等^[52]采用感应钎焊工艺在 60Si2Mn 钢基体表面制备了金刚石/Ni-Cr-B-Si 复合涂层,与电弧熔覆涂层、等离子堆焊 WC 涂层相比(图 14),金刚石钎涂涂层厚度较薄、组织均匀且表面粗糙度较小,其土壤粘附率为电弧熔覆旋耕刀和等离子堆焊旋耕刀的 53.3% 和 70.2%,且磨损失重显著低于其他两种涂层,在实现减粘降阻目标的同时,有效延长了刀具的田间使用寿命。



图 14 不同工艺制备的旋耕刀

Fig. 14 Rotary tillage knives prepared by different processes

(3) 化学热处理

针对农业机械触土部件土壤粘附严重的问题,曾舜柯^[53]采用液相等离子碳氮共渗(PEC/N)技术,对 20 钢为基材的移栽器表面进行改形处理,获得具有微纳孔洞结构的 C、N 共渗层,利用表面微纳孔洞原位负载镁铁水滑石(Mg-Fe/LDHs)粒子并接枝十六烷基三甲氧基硅烷(HDTM)构建了疏水涂层。PEC/N 处理形成的微纳粗糙结构为后续改性提供了结构基础,负载的 Mg-Fe/LDHs 粒子封闭了微孔并提升耐磨性,HDTM 有机功能团通过缩合反应在表面形成低表面能疏水层,三者协同降低了土壤水膜与界面的接触面积与粘附力。

(4) 电化学沉积

GUAN 等^[54]在 Q235 钢旋耕刀表面采用静电喷涂和化学复合镀的方法分别制备了聚四氟乙烯(PTFE)和 Ni-P-PTFE 涂层,并采用物理气相沉积方法制备了 TiAlN 和 CrN 涂层作为对比(图 15),通过试验对比分析了不同工艺和涂层材料的耐磨性和抗粘附性能。结果表明 PTFE 和 Ni-P-PTFE 涂层具有更好的耐磨性和抗粘附性能。

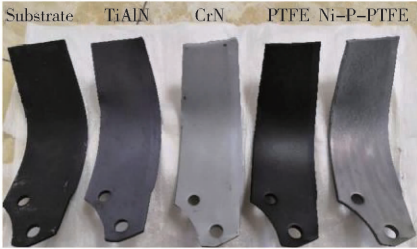


图 15 不同表面处理工艺的旋耕刀实物图

Fig. 15 Physical images of rotary tiller blades with different surface treatments

金刚石钎涂涂层制造成本高、仿生结构设计难度大,激光表面处理设备虽能实现高精度的仿生结构,但投入成本高昂,且仿生结构在作业过程中易磨损失效;化学镀涂层工艺复杂,镀液维护成本高,涂层在冲击载荷下易剥落;液相等离子碳氮共渗设备简单,工艺成熟,但减粘效果受含水率影响大。

2.6 仿生减粘脱附

自然界中,穿山甲^[55-56]、蝼蛄^[57-58]、蚯蚓^[59]、砂鱼^[60]等动物在长期演化过程中形成了优异的土壤适应能力,表现出显著的土壤减粘脱附能力^[61]。自 20 世纪 80 年代以来,科研工作者围绕典

型土壤动物开展了系列研究,揭示了其土壤减粘脱附关键机理,主要包括:体表具有非光滑表面结构^[62]、可分泌降低粘附的体液^[63]、体表材料具备疏土特性^[64]以及存在生物电渗效应^[65-67]等。近年来,科研人员围绕农机触土部件开展了大量卓有成效的研究。随着农机作业质量要求的不断提升,触土部件性能优化需求日益迫切。为此,仿生减粘脱附研究逐步拓展至结构、非光滑形态、材料及耦合仿生等领域^[68],并由静态结构仿形向动态过程模拟与作用机理深度融合方向发展,旨在系统揭示减粘脱附内在规律^[69],为农机触土部件性能持续提升提供理论支撑。

2.6.1 结构仿生

ZHANG 等^[70]将穿山甲体表仿生非光滑结构应用于旋耕刀(图 16),构建了湿黏土壤-刀具离散元模型,研究发现,非光滑表面减小了土壤-刀体的实际接触面积,从而降低了粘附力,使得仿生旋耕刀较传统旋耕刀抗粘效果提升 18.81%。

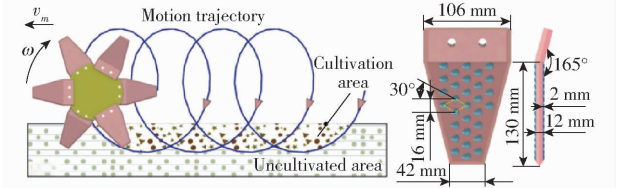


图 16 刀具运动轨迹及仿生结构示意图

Fig. 16 Schematic of tool motion trajectory and bionic structure

王法安等^[71]提取穿山甲前足第三趾的形态特征设计了仿生挖掘铲,研究表明,仿生结构能有效引导土壤颗粒脱离铲面,减少铲面土壤局部堆积和粘附。JIA 等^[72]从动态运动角度提取蚯蚓体表几何特征,设计了仿生镇压轮(图 17),研究发现,蚯蚓通过伸展、静止、收缩之间不断切换来实现运动,体表曲率半径随运动形态变化而改变,当曲率半径较小时,接触面积减小或黏土块被破坏,内聚力与黏附力的平衡被打破;曲率半径低于临界值时,黏土块内聚力超过粘附力,接触面积减小;高于临界值时,黏土块表面首先出现裂纹并随体表持续受压向内扩展,从而破坏土壤-体表界面的稳定粘附,实现脱附。

李健^[73]基于黄牛足蹄设计了抛物线形仿生履带板,结合离散元仿真与土槽试验分析发现,抛物线形履带板通过引导土壤颗粒形成有序高速流场以破坏液体表面张力,同时在界面处诱导形成无土区、微振区和水膜不连续区,降低气体负压作用,增加界面润滑,从而有效降低了土壤粘附。台架试验表明,仿生履带板较传统履带板土壤粘附量降低了 35.15%。

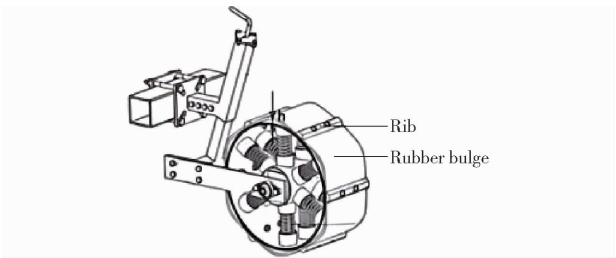


图 17 防粘附结构镇压轮

Fig. 17 Press roller with anti-adhesion structure

2.6.2 非光滑形态仿生

DAI 等^[74]、石方刚等^[75]通过研究蛞蝓运动行为及体表波纹状非光滑结构发现,蛞蝓运动时体表产生动作电位,电渗效应使界面水分迁移,破坏水膜的连续性。其非光滑结构在与土壤接触时,表面无法完全贴合,在微观尺度上形成空气膜,将连续水膜切割为不连续的水环。蛞蝓体表具有疏水性,使水膜难以铺展,呈球状收缩,减少水膜与表面的粘附功,降低了土壤粘附。WU 等^[76]以蚁狮幼虫为研究对象,运用流体力学与斯特劳哈尔数模型分析发现,在土壤运动过程中,部件表面的非光滑结构会对土壤颗粒产生持续扰动,显著增大土壤的疏松指数,内摩擦指数随疏松指数的增大而显著降低,减小了土壤颗粒之间以及土壤-部件表面的内摩擦与粘附力。NIU 等^[77]基于鲨鱼皮鳞片轮廓曲线形态,设计了连续型与非连续型两种仿生结构深松铲,通过仿真与土槽试验对比分析其防粘效果发现,非光滑仿生结构使土壤与仿生结构表面接触部位的应力分布不均,导致难以形成有效粘附,沟槽结构对土壤具有引导与疏通作用,非连续的沟槽易于切断积聚在铲面的土壤,通过断槽将土壤更快地排出,从而有效抑制土壤在铲面堆积与粘附。针对水稻直播机滑板存在的粘附严重、阻力大的问题,张国忠等^[78-79]以泥鳅体表非光滑鳞片结构为仿生原型,通过仿真分析发现,非光滑结构导致其附近区域的流体形成涡旋,产生了困水区域,流体的流速降低,从而抑制湍流猝发,且区域内的液体起到了一定的润滑作用,最终实现减粘降阻。苏文等^[80]、罗震等^[81]、SALEM 等^[82]基于蛞蝓体表非光滑凸包的特征参数,设计了仿生起垄刀(图 18)和栽植器(图 19),研究发现,非光滑凸包结构能够减小土壤与部件表面的实际接触面积、破坏界面水膜的连续性,并在部件与土壤间形成空气膜,进而形成复合界面,达到减粘的效果,但凸包尺寸过小或过大则难以形成稳定界面或导致土壤卡滞,反而加剧粘附。

LIU 等^[83]提取收缩状态下蚯蚓头部的波纹形非光滑表面特征,设计了仿生芯铧式开沟器。研究表明,波纹结构可在开沟器表面与土壤颗粒之间形

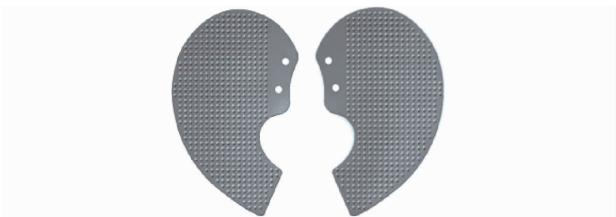


图 18 仿生凸包起垄刀三维模型

Fig. 18 3D model of a bionic convex ridge knife

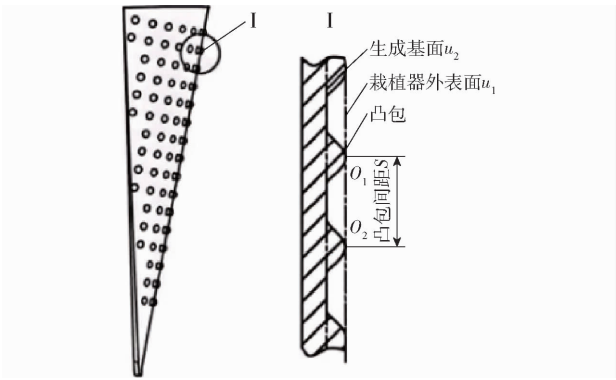


图 19 仿生栽植器三维模型

Fig. 19 Three dimensional model of bionic planter

成间隙,减少实际接触面积与接触土壤的颗粒数量,波纹结构还可引导土壤颗粒沿垂直方向运动,将颗粒对开沟器表面的集中作用力分散至整个表面,缓解应力集中,降低粘附与阻力。

2.6.3 材料仿生

ZHANG 等^[84]通过分析 3 种蚯蚓的表皮黏液的氨基酸组成与流变行为,提出蚯蚓运动中的“五层界面接触模型”,从流变学角度系统揭示蚯蚓黏液的动态减粘降阻机制。邹亮亮等^[85]基于蚯蚓体表波纹结构并引入主动润滑系统,设计了仿生深松铲铲尖(图 20),其利用蚯蚓体表波纹结构约束润滑介质,使界面摩擦由固-固接触转变为固-液-固混合模式,波纹结构还可破坏土壤与铲体的连续接触,降低空气负压吸附,从而达到减粘降阻的效果。

李俊伟等^[86]将白茅根膜质叶鞘的波纹结构与

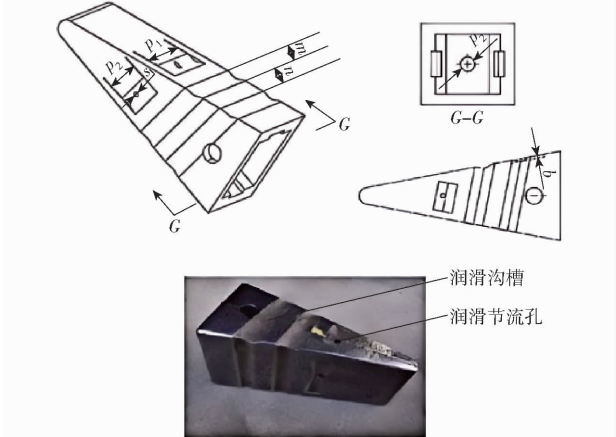


图 20 主动润滑减阻曲面深松铲铲尖

Fig. 20 Design drawing of subsoiler tip

低表面能 PTFE 涂层相结合,设计了仿生马铃薯挖掘铲,波纹结构可减少铲体与土壤的接触面积,破坏界面水膜的连续性,降低土壤对铲体的粘附力。GUAN 等^[87]以獾爪结构为仿生原型,采用 PTFE 与氟硅丙烯酸树脂进行表面改性,显著提升了刀齿在高湿黏重土壤条件下的抗粘附性能。王虎存等^[88]基于西北鼯鼠头部形态设计了仿生楔形挖掘铲(图 21),并通过超高分子量聚乙烯(UHMWPE)进行低表面能修饰,削弱了土壤与金属界面的粘附力,抑制了土壤的吸附与堆积,具有减粘脱附效果。

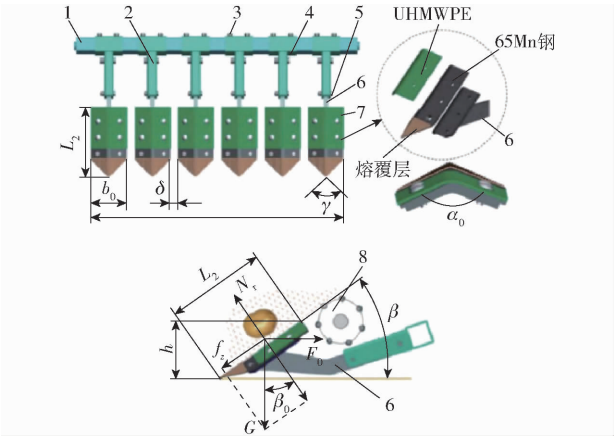


图 21 仿生楔形挖掘铲装置

Fig. 21 Biomimetic wedge-shaped digging shovel device
1. 铲架 2. 过载保护架 3. 限位螺丝 4. 托架固定销 5. 过载剪切销 6. 托架 7. 仿生楔形挖掘铲 8. 栅条碎土辊 I

LIU 等^[89]基于步甲凸包形态设计了仿生镇压轮,采用 UHMWPE 进行表面改性,该镇压轮较传统棱纹轮土壤粘附质量降低约 51.2%;LU 等^[90]以蛭螂体表凸包为原型,同样选用 UHMWPE 设计了凸包型仿生镇压轮,并将其集成于星齿凹盘式覆土装置中,该装置的土壤粘附量较 V 形镇压装置降低 43.68%。上述研究表明,通过提取生物体表非光滑结构的形态特征,并结合低表面能、高耐磨材料进行仿形制备,可实现触土部件的减粘脱附。

2.6.4 耦合仿生

(1) 二元耦合

针对联合收获机履带粘附土壤严重的问题,YUAN 等^[91]基于鸵鸟足部与蛭螂体表非光滑结构特征,分别设计了仿生履带齿与仿生履带板。研究表明,仿鸵鸟足部结构显著提升了单位重量牵引力,仿蛭螂非光滑表面与湿黏土壤形成复合界面,具有减粘效果,系统提升了履带综合通过性。王晓阳等^[92]耦合砂鱼鳃的微刺-鳞片结构与克氏原螯虾的微刺-凸包结构于深松铲铲尖,与土壤作用过程中,微刺结构引导土壤在铲尖优先积聚形成覆盖层,降

低了铲尖对后半部分的土壤粘附。LI 等^[59]将蛭螂体表波纹与扇贝壳棱纹耦合于铲面结构(图 22),蛭螂体表波纹结构能减少土壤与部件间的实际接触面积,破坏界面水膜连续性,从而降低单位面积土壤粘附力,扇贝壳棱纹结构使土壤颗粒在接触铲面时沿特定方向滚动,促进土壤流动,减少土壤在触土表面的附着。

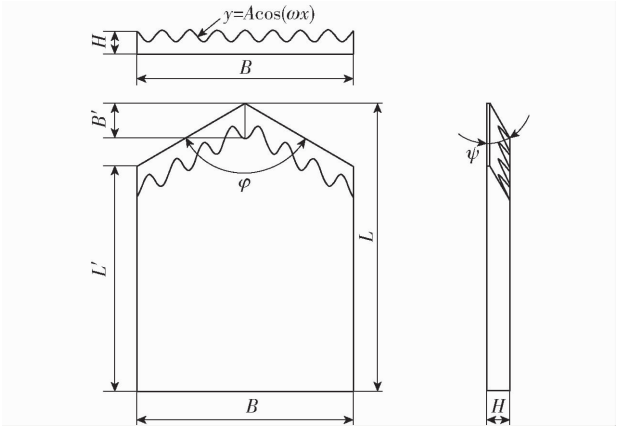


图 22 仿生波纹铲结构示意图
Fig. 22 Schematic of bionic longitudinal wave shovels structure

刘进宝等^[93-94]将穿山甲体表的鳞片三角圆弧状结构和蛭螂体表的凸包结构相结合,对表面轮廓结构尺寸进行比例放大,沿着土迹线依次排列在犁壁上,田间试验结果表明,仿生减粘犁体相对传统犁体土壤减粘性能提升 44.15%。WANG 等^[95]通过气压主动裂土以破坏土壤内部结构、降低其密实度与粘附力,同时结合獾爪与穿山甲鳞片形态特征引导土壤流动并减少接触面积,从而改变土壤与铲面的相互作用状态,减少了土壤粘附。

(2) 多元耦合

DESHMUKH 等^[96]将水牛蹄曲面形状、竹鞘叶宏观纹理和蛭螂锯齿状凸包耦合于水田叶轮表面,并将非光滑仿生宏观纹理与表面工程技术相结合,具有良好的减粘效果。冯超等^[97]融合翠鸟喙部流线型轮廓、野猪吻突出曲线以及蛭螂体表凸包非光滑表面设计了仿生栽植器,蛭螂体表凸包非光滑表面可减少土壤接触面积,仿生栽植器在土壤含水率为 21.3% 时,较原型栽植器土壤粘附量降低 27.4%。

仿凸包、波纹或沟槽等结构制造工艺简单,易于实现,无附加能耗,但减粘效果依赖表面微观结构,受土壤类型、含水率影响较大,微观结构的精准复现对加工精度要求高,导致制造成本提高,作业过程中结构易磨损或变形,长期服役稳定性差。低表面能涂层修饰可提升减粘性能,但减粘效果依赖涂层的耐久性,导致制造难度与成本提高,涂层耐磨性不

足、与基体结合强度低,在长期作业中易磨损剥落。仿蛭蠕电渗技术需额外布设电极与控制系统,仿蚯蚓主动润滑技术需配备润滑液输送系统,均增加了结构复杂性、成本与能耗。耦合仿生通过多生物特征的协同增效,提升了减粘脱附效果,拓宽了工况适应性,但设计、制造及装配精度要求更高,整体结构复杂性与能耗水平亦相对上升。

3 存在问题分析

针对农机触土部件减粘脱附,近年来科研工作者开展了大量卓有成效的研究,较好地满足了我国农机装备的高质量发展需求,但现有技术体系仍有较大的提升空间。

振动减粘、气动减粘、加热减粘、结构减粘等技术虽能有效降低土壤粘附,但需额外配置动力源或辅助系统,致使整机结构复杂、能耗提升。此外,该类技术的振动频率、气压及温度等关键参数多基于特定土壤条件进行优化,针对不同土壤类型及含水率、不同类型触土部件及其作业参数的适应性尚缺乏系统性研究,严重制约了其大规模应用与推广。

表面技术减粘脱附虽能够制备出具有优异初始减粘性能的涂层,但其在实际作业过程中,极易受磨粒磨损、机械冲击等作用而出现减粘脱附性能衰退。目前大多研究过分关注涂层单一性能优化,尚缺乏对耐磨与减粘协同提升的系统研究。在制备工艺层面,激光熔覆、金刚石钎涂等制备工艺成本高;而聚合物涂层等低成本工艺,则存在结合强度低及耐磨性能差等问题。上述问题共同导致现有表面减粘脱附技术难以满足触土部件对力学强度及服役寿命的要求。

仿凸包、波纹或沟槽等结构制造工艺简单,易于实现,无附加能耗,但减粘效果依赖表面微观结构,受土壤类型、含水率影响较大,微观结构的精准复现对加工精度要求高,导致制造成本提高,作业过程中结构易磨损或变形,长期服役稳定性差。低表面能

涂层修饰可提升减粘性能,但减粘效果依赖涂层的耐久性,导致制造难度与成本提高,涂层耐磨性不足、与基体结合强度较低,在长期作业过程中易磨损剥落。仿蛭蠕电渗技术需布设电极与控制系统,仿蚯蚓主动润滑技术需配备润滑液输送系统,均增加了结构复杂性、成本与能耗。耦合仿生通过多生物特征的协同增效,提升了减粘脱附效果,但设计、制造及装配精度要求更高,整体结构复杂性与能耗水平亦相对上升。

4 展望

触土部件作业工况恶劣,土壤粘附机理复杂。提高农机触土部件的减粘脱附性能,延长其使用寿命,对于推动农业机械化及农机装备产业转型升级具有重要意义。为进一步提高农机触土部件的减粘脱附性能,加快中高端减粘触土部件国产化替代进程,全面提升我国农业机械作业质量和效能,未来研究可重点聚焦以下方向:

(1)在粘附机理及振动、气动减粘技术领域,开展动态、多场耦合条件下土壤-部件界面的粘附失效理论研究,构建适用于不同土壤类型及含水率、不同类型触土部件及其作业参数间的普适性预测模型,研发低功耗、自适应振动与气动减粘系统,融合传感器与智能控制技术以实现关键参数的实时精准调控。

(2)在涂层材料体系方面,重点研发兼具低表面能、高耐磨性及强界面结合力的触土部件专用减粘材料,开发多性能复合涂层设计方法及其配套的低成本、环境友好型涂层制备工艺,加强涂层-基体界面结合与长效耐磨-减粘协同机制研究,提升涂层在复合失效模式下的长效服役性能。

(3)在部件仿生设计方面,推动从静态仿形向动态功能仿生转变,融合生物多机制耦合特征,实现低粘附、低成本、高可靠的一体化结构创新。开展仿生部件与整机动力、传动及控制系统的匹配性研究,进一步优化仿生部件的减粘脱附性能。

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