

## Designing technologies for strengthening tractor and self-propelled machine parts in agricultural conditions

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**Abstract.** The study aimed to theoretically substantiate a reproducible engineering approach to selecting reinforcement routes, incorporating transitions between degradation mechanisms and spatial heterogeneity of requirements within a part. The methodology was based on sequential transfer of operating conditions into a cause-and-effect chain “operating conditions – degradation mechanism – critical zone – surface and core requirements – class of technological solution” based on international regulatory requirements for steels, parameters of strengthened layers, corrosion resistance and durability of components. Results showed that the risk of degradation is threshold-based: when one factor is intensified, it increases moderately and is concentrated mainly in a 2-3 point zone of integral scale, while simultaneous intensification of two or more factors shifts the system to a 4-5 point zone due to synergy of corrosion-abrasive and abrasive-fatigue processes. A change in “leading” mechanism has been identified, from predominantly fatigue under moderate conditions to the dominance of surface combined scenarios under high conditions, when the stability of the surface layer and its chemical resistance become decisive. The study substantiated that there are no universal technologies: for parts with a critical core role, volumetric thermal routes are a priority; for contact areas with soil – local surface strengthening and wear-resistant layers; for contact-stressed areas – thermochemical solutions; for wet agrochemically active environments – barrier protection. The

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study demonstrated that additive restoration can be used as a preparatory stage with subsequent post-processing and strengthening, since a reinforced surface layer determines the resource. The practical significance lies in the fact that the generalised model can be used by design engineers, technologists and agricultural service providers when designing and restoring tractor and self-propelled machine parts to select a strengthening route class by correlating operating conditions with the dominant degradation mechanism and the critical area of the part, which reduces accelerated wear

**Keywords:** mechanical loads; degradation; abrasive wear; surface layer; technological route; additive manufacturing

## INTRODUCTION

Modern tractors and self-propelled agricultural machines operate under conditions of intensive agricultural use, which combines high mechanical loads, cyclic impact, abrasive wear from contact with ground, as well as prolonged exposure to moisture and chemically active substances, in particular mineral fertilisers and plant protection products. Under such conditions, service life and reliability of parts are largely determined not only by design solutions, but also by rational engineering of technologies for strengthening surfaces and the material basis of assemblies. Therefore, theoretical analysis of technologies for strengthening parts of tractors and self-propelled machines is becoming increasingly relevant in the context of increasing their durability and reducing operational losses.

O. Zubiekhina-Khaiiat (2017) considered surface plastic deformation processes as efficient tools for improving wear resistance of threaded and worm surfaces widely used in agricultural machinery components. The study showed that controlled formation of a hardened surface layer can significantly reduce wear intensity without changing the geometry of a part. Further development of this direction is demonstrated in a study by O. Zubiekhina-Khaiiat & D. Marchenko (2018), which analyses the rigidity of the “machine tool – tool – part” system during the repair of parts using surface plastic deformation methods. The results confirmed that the effectiveness of strengthening in the context of agricultural machinery restoration largely depends on the stability of the technological system and the correct selection of processing modes. The issue of restoration and strengthening of worn parts was also considered by O. Lyman & D. Marchenko (2022), which substantiates prospects for the use of electric arc restoration coatings in the repair of machines and mechanisms. The authors emphasised that such coatings are suitable for parts that operate under conditions of intense abrasive and corrosive wear, which is characteristic of an agricultural environment. Furthermore, in studies by G. Filimonikhin *et al.* (2021), the analytical approach to assessing dynamic loads in mechanical systems emphasises the need to consider real operating

conditions when designing reinforced elements of rotating machine components.

V. Hruban *et al.* (2025) used finite element analysis methods to assess stress-strain state and optimise designs of agricultural trailed machines to compare design parameters with load-bearing capacity and strength indicators of elements. The results showed that a combination of rational design, adequate choice of materials and strengthening technologies can significantly increase the durability of elements operating in harsh field conditions. Modern approaches to surface strengthening are actively developing in the direction of functional coatings application. In particular, A.S. Kairov *et al.* (2022) showed that composite nano-coatings can significantly increase the wear resistance of tools by forming multilayer structures with improved tribological properties. The study also emphasised that this effect is manifested not only in a reduction in wear intensity, but also in an increase in technological productivity due to stabilisation of friction conditions and a reduction in contact losses. Similar trends are notable in a comprehensive review by C. Munteanu *et al.* (2025), which analysed the use of atmospheric plasma spraying to increase the durability of boron discs. The authors concluded that such coatings are effective for soil cultivation implements that are subject to intense abrasive wear. Thermal and thermochemical strengthening methods remain the basis for mass-produced agricultural machinery parts. D. Romek *et al.* (2024) addressed use of thermally applied coatings to reduce wear on agricultural machinery components, confirming feasibility of combining heat treatment with surface layers to achieve an optimal balance between hardness and toughness. An analysis of operating conditions of self-propelled hydromeliorative machines conducted by A. Formato *et al.* (2022) showed that prolonged operation in a humid environment places increased demands on corrosion and fatigue resistance of components. Accordingly, stability of such machines is determined by the ability of materials and hardened surface layers to maintain their load-bearing capacity and wear resistance under prolonged loads. A systematic review

by J. Hao *et al.* (2024) addressed the state of research on strengthening the wear resistance of soil-contact components of agricultural machines. The study summarised results regarding thermal, laser and coating technologies, emphasising that the greatest effect is achieved through a comprehensive approach that combines material selection, local surface strengthening and adaptation of technology to specific agricultural operating conditions.

Thus, analysis of scientific sources showed that the design of technologies for strengthening tractor and self-propelled machine parts should be based on consideration of actual agricultural loads, the nature of wear and tear, and the aggressiveness of the environment. A combination of classical thermal methods, modern surface coatings, laser technologies and the prospects of additive manufacturing (AM) forms a scientifically sound basis for increasing the service life and reliability of agricultural machinery under conditions of intensive use. The study aimed to develop and theoretically substantiate a universal, reproducible approach to the selection of strengthening technologies, which determined the optimal route incorporating critical thresholds of degradation mechanisms and different requirements for properties of the surface and core of a single part.

Primary study objectives included: generalisation of mechanisms of wear and corrosion of parts in agricultural operation and correlation with requirements for hardened layer; analysis of hardening technologies relevant to agricultural machinery, in particular quenching and tempering, laser surface hardening and nitriding/nitride coatings for corrosion-prone components (pipes, pump housings); identification of approaches to selection of materials (alloy steels, chromium-containing alloys) and prospects for application of additive technologies (3D printing) for manufacture of wear-resistant components with increased requirements for accuracy and strength.

## MATERIALS AND METHODS

The material basis included international regulatory, technical documents and software tools for engineering information processing, which provided a documented justification for the selection of materials and technologies for strengthening tractor and self-propelled machine parts for use in agricultural operations. Basic source of requirements for steels intended for hardening and tempering was ISO 683-1:2016 (2016) standard, which was used for normatively correct coordination of non-alloy steel grades with expected properties of parts under high mechanical loads and intensive abrasive wear in field conditions. For groups

of alloy steels characteristic of critical elements of transmission and power units, ISO 683-2:2016 (2016) was applied, which provided a documentary basis for comparing the choice of material with the need for increased hardenability, stability of structure after tempering and ability to operate under cyclic loads. Since agricultural exploitation is characteristic of direct contact of working surfaces with soil, abrasive particles and corrosive environments, a documentary basis for description and control of surface-hardened layer parameters was formed by ISO 18203:2016 (2016). Its provisions are used for a unified interpretation of the thickness of the surface-hardened layer as a characteristic that determines the performance of parts in modes of abrasive and contact-abrasive wear. To address corrosive effects of moisture, mineral fertilisers and pesticides (critical for pipes, pump housings and housing elements), ISO 9227:2022 (2022) was used as a regulatory basis for comparing corrosion resistance of materials and coatings using a unified salt spray test procedure. General regulatory context for selection of anti-corrosion systems and principles of their application for steel elements were based on ISO 12944-1:2017 (2017) was used to justify the resource suitability of rolling and connection units of variable loads with the durability of aggregates. Prospects for the use of additive technologies (3D printing) for the manufacture or restoration of wear-resistant components were considered based on ISO/ASTM 52900:2021 (2021), which provides terminological and classification consistency in AM. ISO/ASTM 52920:2023 (2023) was used to justify industrial reproducibility of such solutions and requirements for qualification of processes and production sites. This method was used to correctly formulate criteria for the applicability of additive manufacturing/restoration specifically for agricultural machinery parts, incorporating requirements for quality, stability and repeatability of production results.

Research methodology was based on a combination of logical-analytical and systematic approaches, which provided new generalisations regarding the design of technologies for strengthening parts for agricultural use. The research was conducted as a sequential procedure of interpreting documentary requirements and transferring them into applied engineering logic for the selection of technologies based on the principle of 'working conditions – degradation mechanism – requirements for the surface and core – technological strengthening route – expected resource effect'. The first stage involved logical identification of typical agricultural operating conditions that determine degradation of parts: high contact and bending

loads, abrasive wear on contact with soil, corrosive and abrasive action in a humid environment, and the influence of chemically active substances. Within this stage, to ensure reproducibility of interpretation of operating conditions, a conditional risk scaling was applied along three axes of influence: mechanical load, abrasiveness of soil contact, and corrosive activity of the environment. The levels “low/medium/high” were set as qualitative engineering categories: “low” corresponded to modes without prolonged peak loads and impact, with occasional contact with abrasives and limited moisture; “medium” corresponded to modes of regular operation with variable loads, stable abrasive contact and periodic moistening; “high” corresponded to modes combining significant contact/impact-cyclic loads with intense abrasive action and prolonged exposure to moisture and agrochemical agents.

An integral risk score of 1-5 was formed as a generalised assessment of a combination of three levels: when one “high” factor dominated, risk was usually classified as zone 2-3, while simultaneous intensification of two or more factors moved the assessment to zone 4-5, which was interpreted as a threshold transition to combined degradation scenarios. On this basis, a list of dominant damage mechanisms (abrasive wear, contact fatigue, corrosion damage, combined mechanisms) was formed, which was subsequently used as a “filter” for the appropriate selection of strengthening technologies. At the second stage, a systematic comparison of technological strengthening approaches with groups of tractor and self-propelled machine parts was conducted. Thermal strengthening (hardening and tempering) was interpreted as basic route for parts in which load-bearing capacity and fatigue endurance in cross-section are critical (shafts, axles, gear elements), while local strengthening methods were considered appropriate for working areas with concentrated wear or local contact stresses (seats, edges, contact paths), where it is necessary to increase hardness without significantly changing the properties of the core. Protective solutions against corrosion and corrosive-abrasive wear were considered a priority for components operating in wet and chemically active environments (pipes, pump housings, housing parts), with a focus on improving corrosion resistance and surface stability. In the third stage, the model was developed based on criteria of intensity and combination of operational factors, the dominant degradation mechanism, localisation of the critical zone in the part, and distribution of requirements between the surface and core, as well as based on reproducibility and technological compatibility of the route. The results of structuring the conditions of agricultural operation were integrated

by linking typical combinations of load, abrasiveness and corrosive activity to damage mechanisms and then transforming this link into a transition rule “condition → mechanism → critical zone → requirement profile → technology class”. The choice of technologies was determined for each group of parts according to what limits the resource: for power elements with a decisive role of the core, priority was given to volumetric routes; for soil-contact and friction zones – to local surface strengthening and wear-resistant layers; for contact-stressed zones, solutions combining a hard surface with a viscous base were given priority; for parts in a humid agrochemically active environment, protective barrier approaches were given priority, and additive restoration was introduced only as a preliminary stage of geometry restoration with mandatory post-processing and subsequent strengthening of working surfaces.

Generalised correspondence graphs were constructed in MATLAB and Microsoft Excel. In MATLAB, correspondence rules were formalised in the form of parameterised tables and functional dependencies (for transparency of logical transitions and reproducibility of the decision-making scheme), while Excel was used for tabular coordination of parameters and visualisation of results in the form of diagrams and correspondence matrices “degradation mechanism – technology – expected effect”.

## RESULTS

### Structuring of agricultural exploitation conditions as factors of component degradation

The results of interpreting agricultural operating conditions showed that the degradation of tractor and self-propelled machine parts is caused not by individual factors, but by their stable combinations, which determine the dominant mechanisms of damage and the rate of loss of working capacity. Unlike stationary or industrial machines, agricultural machinery operates in an environment with highly variable loads and external factors, which causes a transition from single-factor to combined degradation scenarios. The analysis showed that mechanical loads, abrasive action of soil and corrosive activity of the environment act simultaneously, but with varying intensity depending on the type of operation, season and functional purpose of the part. This made it possible to consider operating conditions as a structured system of factors rather than a set of separate influences. To summarise the identified patterns, Table 1 was created, which reflects the characteristic conditions of agricultural operation and their engineering consequences for the degradation of parts.

**Table 1.** Characteristics of agricultural operating conditions and engineering implications for the degradation of tractor and self-propelled machine components

Nature of operating conditions	Engineering manifestations of the environment	Dominant mechanical influences	Main mechanisms of component degradation	Typical risk areas
Low loads, dry conditions	Low humidity, no aggressive impurities	Moderate static and variable loads	Fatigue damage with slow accumulation of defects	Shafts of auxiliary mechanisms, body elements
Medium loads, moderate abrasiveness	Contact with soil particles, periodic moistening	Contact and bending loads	Abrasive wear with local plastic deformation	Seating areas, support surfaces
High loads, dry abrasive environment	Intensive action of mineral particles in the soil	High contact stresses, shock loads	Abrasive and contact-abrasive wear	Gear transmissions, working edges
Moderate loads, high humidity	Prolonged contact with moisture, agrochemicals	Variable loads of medium level	Corrosion and corrosion-fatigue damage	Pipes, pump housings, housing parts
High loads, moisture and abrasion	A combination of soil, moisture and chemically active components	High contact, bending and cyclic loads	Corrosion-abrasive wear, accelerated contact fatigue	Working surfaces of power and transmission units
Combined extreme conditions	Simultaneous action of abrasives, moisture and chemical agents	Multi-axis variable loads	Combined degradation mechanisms with nonlinear wear growth	Critical elements of transmissions and friction units

**Source:** compiled by authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

Analysis of Table 1 showed that under conditions of moderate loads and low abrasiveness, degradation of parts is mainly fatigue or corrosion in nature and develops relatively slowly. When transitioning to modes of intensive interaction with soil, especially in conditions of high humidity and the presence of chemically active components, a sharp increase in the rate of wear is observed. Under such conditions, abrasive and corrosive effects are superimposed on mechanical stresses, forming combined damage

mechanisms, in particular corrosive-abrasive wear and accelerated contact fatigue. Most vulnerable are working surfaces of parts that simultaneously receive loads and contact aggressive environments, while massive elements with less surface impact degrade more slowly but accumulate hidden fatigue damage. To illustrate the interaction of key degradation factors, a matrix visualisation of risks has been constructed to identify areas of transition from simple to combined damage mechanisms (Table 2).

**Table 2.** Matrix of risks of part degradation depending on the combination of mechanical loads, abrasive and corrosive effects

Corrosive effect/Mechanical loads	Low	Average	High
Low	1	2	3
Average	2	3	4
High	3	4	5

**Note:** abrasive impact reflected in the integral risk assessment (1-5)

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

The heat map in Table 2 showed that the integral risk of degradation increases from 1-2 points (low risk) in combinations of “low/medium loads + low abrasiveness + low corrosive influence” to 4-5 points (high risk) in the zone where all three factors are high. In transitional cells, where only one factor is “high” (e.g., high abrasiveness with medium loads and medium corrosion), risk is concentrated mainly at 3 points, i.e., the matrix shows that isolated intensification of one factor results in a moderate increase in risk, while combined intensification of two or more factors moves the system into the 4-5 zone. The key engineering pattern is that when moving from “one high

factor” to “two high factors”, risk does not increase linearly (by 1 point, for example), but jumps to the upper range of 4-5, reflecting the synergistic nature of combined damage mechanisms (abrasive fatigue and corrosion abrasion).

A generalisation of the structuring of agricultural operating conditions has shown that degradation of tractor and self-propelled machine parts is mainly a result of a combination of mechanical loads, abrasive action of soil and corrosive activity of the environment, rather than the isolated effect of a single factor. Under conditions dominated by load alone, abrasion alone, or corrosion alone, damage develops relatively predictably within a single

mechanism, whereas simultaneous intensification of several factors shifts working surfaces into a zone of combined scenarios with accelerated wear and fatigue exhaustion of the material. Established pattern means that engineering-correct choice of strengthening technologies should be based on identification of dominant combinations of factors for a specific group of parts and should ensure not only increased hardness, but also stability of surface layer and resistance to corrosion-abrasive interaction in conditions of moisture and chemically active agents.

### Identification of dominant damage mechanisms under agricultural exploitation conditions

The study established that in agricultural conditions, degradation of parts rarely occurs through a single

isolated mechanism. Instead, scenarios prevail in which basic mechanisms – fatigue damage, abrasive wear or corrosion – interact with each other, forming combined types of destruction. The nature of this combination depends on the functional purpose of the part, the nature of contacts, the load regime, and the duration of exposure to an aggressive environment. Therefore, identification of the dominant mechanism is considered not as classification “by feature”, but as an engineering tool for preliminary selection of strengthening technologies. To summarise results and formalise transitions between mechanisms, a comparative characteristic of dominant degradation scenarios is presented in Table 3, which can be used to compare them by damage location, load nature and material property requirements.

**Table 3.** Comparative characteristics of dominant mechanisms of degradation of tractor and self-propelled machine parts and their engineering consequences

Dominant mechanism of degradation	Typical location of damage	Nature of loads	Key operating conditions	Engineering requirements for part properties
Fatigue damage	Cross-section of a part, stress concentration zones	Variable, cyclic, bending and torsional	Relatively dry conditions, moderate abrasiveness	High fatigue resistance of the core, structural stability
Abrasive wear	Working surfaces, edges, and areas in contact with the ground	Contact, impact, local	Intensive contact with soil, dry abrasive environment	Increased surface hardness, wear resistance
Contact abrasive wear	Seating positions, gear couplings	High contact stresses	A combination of loads and abrasive action	High surface hardness while maintaining a strong core
Corrosion damage	Surfaces with prolonged contact with moisture	Moderate variable loads	High humidity, agrochemicals	Corrosion resistance, stability of the protective layer
Corrosion fatigue damage	Cross-section and surface simultaneously	Variable loads of medium level	Wet environment under cyclic loading	Compromise between fatigue strength and corrosion resistance
Corrosion and abrasive wear	Working surfaces of power units	High contact and cyclic	Moisture + soil + chemically active agents	High surface hardness and chemical stability
Combined mechanisms	Critical friction and load zones	Multivariate variables	Simultaneous action of all factors	Comprehensive solutions for surface and core strengthening

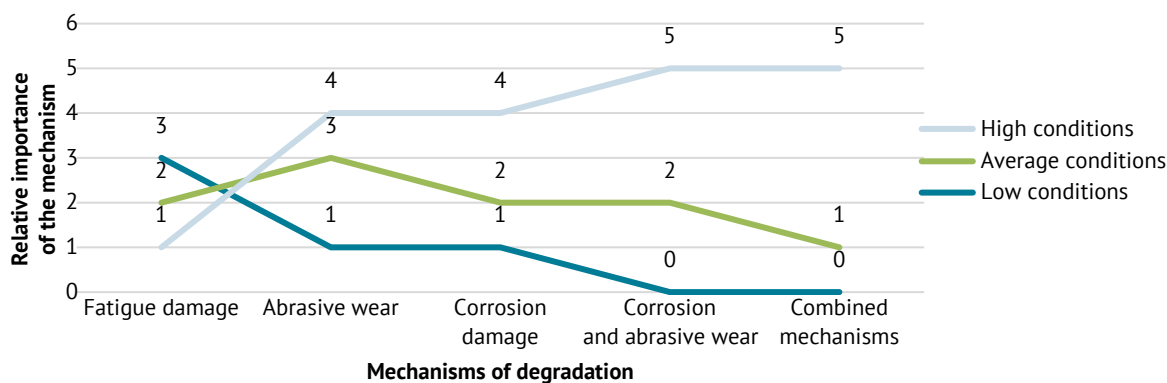
**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

Analysis of the classification presented in Table 3 showed that the transition from simple to combined degradation mechanisms does not occur gradually, but through a change in the dominant damage scenario. Under conditions where one factor significantly prevails, the degradation mechanism remains relatively predictable and localised. However, simultaneous intensification of two or more operational influences causes a qualitative change in the nature of destruction, in which surface and volume degradation processes mutually accelerate each other. Figure 1 shows the priority zones of degradation mechanisms depending on the level of operating conditions and the functional purpose of

the part. Figure 1 showed a shift in the “centre of gravity” of degradation from fatigue mechanisms to surface combined processes as operating conditions change from low to high. Under low conditions, fatigue damage has the greatest relative significance ( $\approx 3$ ), while abrasive wear decreases to  $\approx 1$ , corrosion damage remains at  $\approx 1$ , and corrosion-abrasive and combined mechanisms are practically non-existent ( $\approx 0$ ). In medium conditions, there is a “break” in trend: abrasive wear reaches its maximum ( $\approx 3$ ), while fatigue damage decreases to  $\approx 2$ , and the corrosion-abrasive component stabilises at a moderate level ( $\approx 2$ ), which corresponds to the transition from predominantly volumetric fatigue to dominance of

surface wear in parts that regularly come into contact with soil particles. Further intensification of conditions to high levels causes a jump in priority of corrosion-abrasive wear and combined mechanisms to upper level ( $\approx 5$ ), while corrosion damage remains high ( $\approx 4$ ) and fatigue mechanism falls to a minimum ( $\approx 1$ ). This “change of leader” between medium and high conditions is critical from an engineering

point of view: after a certain threshold of intensity of influences (simultaneous action of loads, abrasives and corrosive environments), degradation ceases to be described by a single dominant process and transitions to a synergistic mode, where rate of performance loss is determined by stability of surface layer and its resistance to corrosive-abrasive interaction, rather than solely by strength of core.



**Figure 1.** Priority areas for component degradation mechanisms, depending on the level of operating conditions and the functional purpose of the component

**Note:** values are presented as conditional priority scores (0-5) obtained through expert interpretation and normative-engineering ranking of dominant degradation mechanisms depending on the level of operating conditions and functional purpose of the part

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

A summary of the results of identifying dominant damage mechanisms showed that tractor and self-propelled machine parts are characterised by a predominance of mixed degradation scenarios, in which basic processes of fatigue exhaustion, abrasive wear and corrosion damage do not exist separately, but form mutually reinforcing combinations depending on the function of the part, the type of contact and the duration of exposure to environment. The study determined that with a change in the operating mode from conditions where cyclic loading is dominant to conditions where surface contact with soil and a wet agrochemically active environment is dominant, there is a change in “leading” mechanism and, accordingly, engineering profile of requirements changes: from priority of resource endurance of core stability of structure to priority of stability of surface layer, hardness and chemical resistance. Therefore, it is advisable to treat the dominant degradation mechanism as an engineering “filter” for preliminary selection of strengthening technologies, which can align the requirements for the surface and core with the actual configuration of operational influences for a specific group of parts.

#### Systematic comparison of technological approaches to reinforcement with groups of parts and working areas

The study established that even within a single component, different areas may be subject to fundamentally different requirements. Surface layers that are in direct contact with soil or aggressive environments require increased hardness, wear resistance and chemical stability, while the core of the part must be able to withstand cyclic and impact loads without losing fatigue strength. This makes it advisable to use technologies that provide a gradient of properties or local strengthening, rather than uniform modification of the entire volume. To formalise this approach, Table 4 has been created, in which groups of parts are compared with the dominant degradation mechanisms and corresponding classes of strengthening technologies.

System analysis Table 4 showed that there are no universal strengthening technologies for agricultural machinery, and effectiveness is determined by the correspondence between the degradation mechanism and the principle of forming the properties of the surface and core. For parts with predominant fatigue damage, technologies that minimise structural

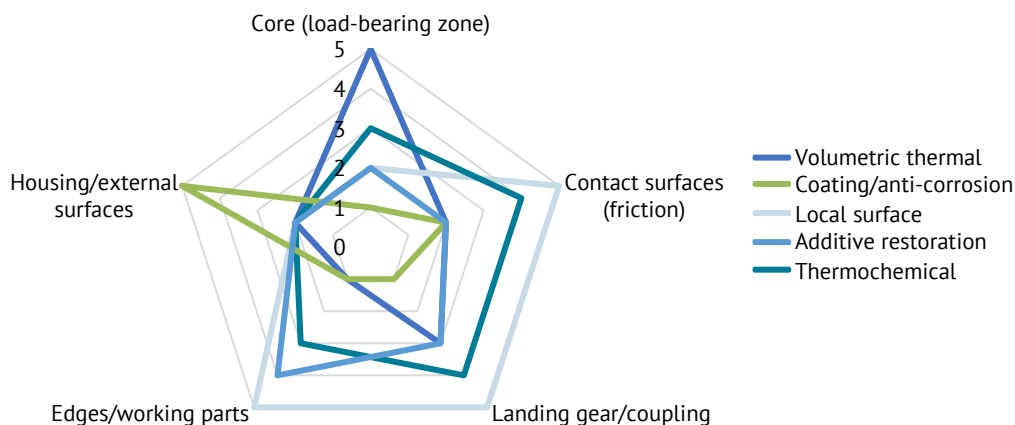
inhomogeneities and residual stresses in the material volume are a priority, while for parts operating in areas of intense contact with the soil, increasing the wear resistance of the surface layer, even at the expense

of limited plasticity, becomes crucial. To illustrate the spatial logic of this approach, a schematic prioritisation of strengthening technologies by functional areas of parts is used (Fig. 2).

**Table 4.** Correspondence of tractor and self-propelled machine parts groups to dominant degradation mechanisms and strengthening technology classes

Group of parts	Key working area	Dominant mechanisms of degradation	Priority requirements for properties	Class of strengthening technologies
Shafts, axles, spindles	Cross-section, stress concentration zones	Fatigue, corrosion fatigue damage	High core fatigue endurance	Volumetric thermal and thermomechanical
Gear transmissions	Contact surfaces of teeth	Contact abrasive wear	Hard surface + strong core	Surface thermochemical
Working edges, knives	Edge, surface in contact with the ground	Abrasive, corrosive-abrasive wear	Maximum surface wear resistance	Surfacing, spraying, composite layers
Housing parts, pipes	Outer surface	Corrosion damage	Chemical stability, surface protection	Protective and barrier coatings
Friction nodes	Contact areas	Combined mechanisms	Resistance to multifactorial degradation	Combined and hybrid technologies

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)



**Figure 2.** Prioritisation of strengthening technologies by working areas of parts

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

Figure 2 showed that the priority of strengthening technologies changes with the transition between working areas of the part. For surface areas that are in contact with ground and operate in friction mode, surface and local methods dominate, indicating a decisive role of wear resistance and stability of the surface layer. In seating and contact areas, the profile becomes more balanced: surface solutions must be reinforced by ensuring the strength of the core, which corresponds to transitional mechanisms of degradation. For areas that operate in bending/torsion, priority shifts to volumetric thermal technologies, since resource is determined by fatigue endurance of material in cross-section.

A summary of systematic comparison of technological approaches to reinforcement with groups of parts and working areas showed that technically correct choice of technology for agricultural machinery

is determined not by the “type of part” as such, but by the configuration of its working areas and dominant degradation mechanisms, which can vary significantly within a single unit. The study established that surfaces that work in contact with soil or in a humid agrochemically active environment require priority of surface layer properties (wear resistance and chemical stability), while areas that are subject to cyclic and impact loads require priority of core properties (fatigue resistance and structural stability), therefore, solutions with localisation of the effect or a gradient of properties are practically expedient. Thus, the effectiveness of strengthening in agricultural use is achieved through the coordination of “working zone – degradation mechanism – surface/core properties – technology class”, rather than through universal application of a single route to the entire volume of the part.

### Justification of the applicability of additive manufacturing and restoration in technological routes for strengthening

Results of engineering analysis showed that additive technologies should be considered not as an alternative to classical strengthening methods, but as a preliminary stage of the technological chain, which can restore geometry, form repair allowance and locally control configuration of material in future contact. Within the scope of the study, additive manufacturing/restoration is interpreted as a stage that only serves a purpose if followed by post-processing and

strengthening, since the surface layer and stability determine the service life of agricultural machinery parts under conditions of abrasive-corrosive interaction. The study established that key conditions for applicability are process repeatability and quality control at the production site, compatibility of the selected additive material with subsequent strengthening methods, as well as an economically justified balance between the cost of restoration and the predicted resource effect. Table 5 presents the generalised criteria for the applicability of the additive stage as a component of the strengthening technological route.

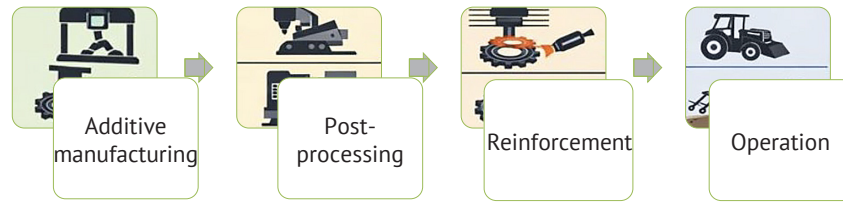
**Table 5.** Criteria for the applicability of additive manufacturing and restoration of agricultural machinery parts with subsequent strengthening of working surfaces

Applicability criterion	Engineering content of the criterion	Potential limitations and risks	Engineering opinion on feasibility
Functional purpose of the part	Determined whether part functions as a load-bearing element, a friction surface or a housing part	Non-compliance of the AM structure with load requirements	Suitable for parts with localised areas of wear or geometric loss
Nature of the dominant mechanisms of degradation	Assessed whether abrasive, corrosive or combined damage prevails	Accelerated deterioration due to incorrect route selection	AM is effective when followed by surface strengthening
Degree of wear or loss of geometry	The possibility of restoring shape without excessive material build-up is analysed	Excess residual stresses, structural defects	Suitable for medium and local wear with controlled allowance
Compatibility of material with strengthening operations	The ability of AM material to withstand thermal and thermochemical processes is tested	Cracks, phase instability, structural degradation	Applicable to steels compatible with subsequent hardening
Requirements for core properties	Assessed whether fatigue strength and structural stability are ensured	Reduction in service life under cyclic loads	AM is justified if the core is not critically loaded
Requirements for the surface layer	The need for high hardness, wear and corrosion resistance is determined	Premature wear without additional reinforcement	AM is considered only as a preliminary stage before consolidation
Repeatability and quality control of the process	Stability of results between batches and sites is analysed	The impossibility of predicting the resource	Application is possible with a qualified process
Economic feasibility	The cost of the AM route is compared with the expected resource effect	No economic gain	Suitable for expensive or hard-to-replace parts
Integration into the existing technological route	Compatibility of AM with post-processing and strengthening is assessed	Complications in the production cycle	Effective as part of a combined route
Repairability and serial production	The possibility of reusing the route is analysed	Limited scalability	Most effective for repair and small-batch tasks

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

An analysis of generalisations in Table 5 showed that the applicability of AM or restoration in agricultural engineering is determined not by the fact that it is possible to “print/build up” material, but by the fulfilment of a set of interrelated conditions that set limits of engineering feasibility of the route. A pattern can be traced: criteria related to working surface (requirements for hardness, wear and corrosion resistance) systematically “pull up” the need for the next stage of strengthening, i.e., AM in the table is interpreted as a preliminary operation of restoring geometry or forming a blank, and resource is determined by the stability of the surface layer after strengthening. At the

same time, criteria describing core (fatigue endurance, structural stability under cyclic and impact loads) act as a limiting filter: when core is critically loaded, the feasibility of AM decreases as the risks of defects and variability of properties affect the resource. Separately, there is a “critical break” between technical feasibility and industrial applicability: even with formal compatibility of material and post-processing, the solution becomes justified only when process repeatability, quality control and integration into the existing technological route are ensured, otherwise the resource forecast becomes uncertain. Figure 3 summarises the sequence of the technological route.



**Figure 3.** Generalised diagram of the technological route  
“additive manufacturing/restoration – post-processing – strengthening – operation”

**Source:** compiled by the authors

According to Figure 3, the technological route is constructed as a sequential integrated scheme in which additive manufacturing or restoration is used to form or restore the geometry of a part, but does not determine service life independently. After the additive stage, post-processing is provided to correct accuracy, reduce roughness and partially stabilise the material structure. Further strengthening of the working areas is aimed at the targeted formation of surface and core properties in accordance with the dominant degradation mechanisms, while the operational stage reflects the implementation of the cumulative effect of all previous operations.

A summary of the results of the justification of the applicability of AM and restoration showed that for agricultural machinery parts, the AM stage is technically justified primarily as a preparatory link in a combined strengthening route, when it is necessary to restore the geometry, form a repair allowance and locally control the configuration of the material in the area of future contact, but final resource is determined not by the “building up”, but by quality of post-processing and stability of strengthened surface layer under conditions of abrasive-corrosive interaction. Key conditions for feasibility are the reproducibility and qualification of the process at the production site, compatibility of the additive material with subsequent strengthening operations, and the technological integration of the route, while for critically loaded elements with a decisive role of core

properties, AM should be considered a limited solution due to the risks of structural variability and defectiveness. As a result, additive manufacturing/restoration should be treated as a tool for improving maintainability and resource efficiency only when it works in conjunction with “AM – post-processing – strengthening”, ensuring a predictable resource effect and an economically justified balance between costs and expected durability.

#### **An integral conceptual model for selecting technologies for strengthening parts for agricultural use**

As a result, an integrated conceptual model for selecting technologies for strengthening agricultural machinery parts has been developed, which transfers the choice of route from a descriptive level to the level of a reproducible engineering rule. The study established that the decisive factor is not the name of the part, but the configuration of the operational impact, which sets the priority for the formation of properties or the core (when the resource is limited by volumetric fatigue), or the surface layer (when the resource is limited by wear and corrosion interaction), and in combined modes – the need to combine strengthening principles in a single route. Table 6 is presented as a formalised “core” of the model, which records these transitions between classes of solutions and provides the same application logic for different groups of parts and working areas.

**Table 6.** An integral conceptual model for selecting technological routes for strengthening tractor and self-propelled machine parts in agricultural conditions

Conditions of agricultural exploitation	Dominant mechanism of degradation	Critical working area of the part	Engineering requirements for properties	Priority technological route for strengthening
Moderate mechanical loads, low abrasiveness, limited moisture	Fatigue damage	Cross-section of a part, stress concentration zones	High fatigue resistance, structural homogeneity of the core, and minimal residual stress	Volumetric thermal or thermomechanical processes without local surface supersaturation
Variable loads during periodic contact with the ground	Abrasive wear	Working surfaces, edges, contact areas	Increased surface hardness, resistance to microcutting and plastic deformation	Surface strengthening or formation of a wear-resistant layer with minimal impact on the core
High contact stresses under dry abrasive conditions	Contact abrasive wear	Gear couplings, mounting locations	A combination of hard surface and tough core, with resistance to contact fatigue	Thermochemical or combined surface-volume technologies

Table 6, Continued

Conditions of agricultural exploitation	Dominant mechanism of degradation	Critical working area of the part	Engineering requirements for properties	Priority technological route for strengthening
Moderate loads in humid and agrochemically active environments	Corrosion and corrosion-fatigue damage	Surfaces with prolonged contact with the environment	Chemical stability, corrosion resistance without loss of mechanical reliability	Protective and barrier coatings or chemical-thermal methods with phase composition control
High loads + moisture + abrasive	Corrosion and abrasive wear	Working surfaces of power and transmission units	Stability of surface layer, preservation of adhesion and resistance to the combined action of the environment and loads	Combined or hybrid technologies with local formation of functional layers
Local loss of geometry while maintaining load-bearing capacity	Combined wear and fatigue mechanisms	Localised areas of contact or wear	Restoration of geometry with subsequent formation of specified surface properties	Additive manufacturing or restoration → post-processing → targeted strengthening of working areas

**Source:** compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)

Table 6 summarised reproducible logic of selecting a reinforcement route based on the cause-and-effect chain “operating conditions → degradation mechanism → critical zone → property requirements → technology class” and showed that a change in the dominant mechanism automatically changes the “focus” of property formation between the core and the surface. For modes where the resource is limited by volumetric fatigue in the cross-section, the solution is reduced to volumetric thermal strengthening with structural stabilisation of the core (typically – hardening and tempering), while with a shift in degradation to working surfaces in contact with the ground, priority is given to surface and local methods that increase hardness and micro-cutting resistance without critically affecting the base (in particular, local laser hardening or the formation of a wear-resistant layer). Under high contact stresses in dry-abrasive conditions, there is a need to combine a hard surface with a ductile core, which justifies thermochemical/combined routes, where nitriding is a technologically relevant example as a way to strengthen contact areas while preserving load-bearing properties. For wet agrochemically active environments, the priority shifts to solutions that provide chemical stability and barrier protection while maintaining mechanical reliability (coating and protective systems), and in the most severe combined scenarios of “high loads + moisture + abrasion”, only hybrid routes that combine wear-resistant strengthening with corrosion protection prove to be effective. A separate row of the model emphasises that additive manufacturing/restoration is not a self-sufficient strengthening method and is used as a restoration stage for parts with local geometry loss, after which the resource is determined by the quality of post-processing and targeted strengthening of working areas.

Generalisation of the patterns of degradation of tractor and self-propelled machine parts in agricultural operation has shown that their service life is determined by stable combinations of mechanical loads, abrasive action of soil and corrosive and agrochemical activity of the environment. Under moderate conditions, degradation is mainly fatigue or corrosion in nature and develops slowly, while intensive contact with soil at high humidity and in the presence of chemical agents thresholds the system into combined scenarios with a sharp acceleration of wear. The study demonstrated that with an increase in abrasive and corrosive components, not only does the strength of the material become critical, but also the stability of the surface layer and its resistance to corrosive-abrasive synergy. A systematic comparison of working areas with technology classes confirmed the absence of universal solutions: for areas where the resource is limited by cyclic stresses, priority is given to core stabilisation routes through thermal strengthening, while for contact areas in soil and wet agrochemically active environments, local surface strengthening, thermochemical and protective approaches are preferred. In the most severe combined regimes, only hybrid routes combining at least two principles of property formation are effective, since a separate increase in hardness or only barrier protection does not cover the range of damage mechanisms. Additive manufacturing/restoration is justified as a preparatory stage for restoring geometry and repair allowance, but the predicted resource is only ensured by the combination of “post-processing – targeted strengthening”, subject to reproducibility and quality control. Overall, the results prove that the engineering choice of strengthening should be based on the configuration of factors, threshold transitions of degradation mechanisms, and spatial heterogeneity of requirements

within a part, which justifies the use of an integral model as a reproducible decision-making rule.

## DISCUSSION

Structuring of agricultural exploitation conditions revealed a threshold nature of degradation: with dominance of one intensive factor, integral risk was concentrated mainly within 2-3 points, while simultaneous strengthening of two or more factors shifted the system to the 4-5 point zone, which was interpreted as a synergistic transition to combined abrasive-fatigue and corrosion-abrasive mechanisms. A similar non-linearity in the increase in the danger of operating self-propelled machines was observed in the conclusions of L. Marrazzina *et al.* (2024), where the riskiness of real field conditions and their ability to quickly accumulate critical states in a technical system were addressed. Change in the dominant degradation mechanisms from predominantly fatigue under moderate conditions to the predominance of surface combined scenarios under high conditions correlated with the fact that the operational heterogeneity of driving modes and vibration-impact components described by T-A. Oncescu *et al.* (2025) formed an uneven load background, which naturally intensified the transition from “core” endurance processes to critical surface stability. A systematic comparison of technological approaches with the working area of the part showed that there were no universal routes and that within a single node, the priorities for strengthening varied between the core and the surface. This conclusion was conceptually supported by a review by E. Fartash Naeimi *et al.* (2025), which emphasised the role of new-generation materials in improving the operational properties of agricultural machinery, but at the same time recognised the need for structural and technological adaptation to specific operating conditions. The effectiveness of local surface solutions in soil contact areas correlated with the results of H. Xiao *et al.* (2025), where laser texturing of working parts made of 65Mn steel demonstrated an increase in wear resistance due to controlled surface modification; in the presented results, a similar logic was manifested in the priority of local strengthening for edges and areas of contact with the soil, when an increase in surface hardness and stability was not accompanied by a critical deterioration in the properties of the core. For components operating in a humid and agrochemically active environment, a shift in the engineering focus to chemical stability and surface barrier properties was demonstrated, as the corrosive component in combination with abrasives caused accelerated synergistic degradation. This interpretation confirmed the conclusions of O.A. González Noriega *et al.* (2025),

where plasma nitriding demonstrated improved corrosion behaviour of steel in conditions simulating soil solution; in the results, this corresponded to the priority of thermochemical solutions for parts such as pipes and pump housings, where the corrosion factor became decisive. At the same time, for parts with a critical core role, routes aimed at increasing fatigue endurance without excessive “oversaturation” of the surface were shown to be expedient, which was consistent with the approaches of S.Q. Lu *et al.* (2024), where shot peening parameters were considered as a tool for controlling the properties of cemented shafts; in the presented technology selection model, this logic was reflected in the priority of volumetric thermal and thermomechanical solutions for shafts, axles and power elements.

In the group of technologies focused on contact stress zones, the need to combine a hard surface and a ductile core was demonstrated, which was explained by the nature of contact abrasive wear and the requirements for resistance to contact fatigue. This position correlated with the results of Z. Satbayeva *et al.* (2024), where electrolytic-plasma nitriding of medium-carbon steel demonstrated improved tribological properties; in the presented conclusions, this corresponded to the expediency of nitriding as a route for seating areas and gear meshes. For soil-contact working edges, the study demonstrated that the greatest effect was expected from coating and surfacing solutions when maximum surface wear resistance was required; this interpretation reflected similar patterns established in Y. Dilay (2023), where nickel-carbide coatings applied by atmospheric plasma spraying increased the wear resistance of cultivator blades. It was emphasised that the effectiveness of plasma and electrolytic-plasma treatments was determined by the control of technological parameters, since they determined the structure and stability of the hardened layer; this thesis correlated with the conclusions of B. Rakhadilov *et al.* (2024) regarding the parametric sensitivity of the mechanical and tribological characteristics of steel after electrolytic-plasma treatment, and the results reflected the requirement for reproducibility and quality control to ensure the predicted resource effect. The generalisation of multifactorial degradation, which addressed material, soil conditions and dynamic regimes, was consistent with the review by A. Yazıcı (2024), in which the wear of tillage implements was considered as a result of the interaction of material properties, soil abrasiveness and contact dynamics. The results were also consistent with the generalisations of N.H. Ameen (2025), where the combined action of corrosion and abrasive wear was considered to be the key mechanism for the accelerated destruction of agricultural machinery parts and the

reason why isolated solutions such as “only increasing hardness” often prove insufficient. A return to the established numerical markers showed that it was the combination of “high loads + moisture + abrasive” that shifted the degradation to a corrosion-abrasion scenario and formed a jump to 4-5, and the engineering conclusion was to prioritise technologies that simultaneously provided wear resistance and chemical stability of the surface, rather than just strengthening the core. This approach correlated with the review by H. Jiang *et al.* (2023), which showed that the stability of self-propelled machines is a function of design configuration and modes, and that changing the load condition when approaching critical modes increases risk factors.

The study demonstrated that the nature of the interaction between the working body and the soil and the choice of operating modes determined which degradation mechanism became dominant and, therefore, determined the selection of strengthening technologies as a “filter” for the critical working area. This logic confirmed the conclusions of S. Rahaman *et al.* (2025), where the analytical design of a self-propelled rotary unit was based on crop parameters and, in fact, on the formation of contact conditions that determine the load and wear of working elements. Additional confirmation of this was provided by the experimental conclusions of L. Tian *et al.* (2022), where the “wheel-soil” interaction was taken as the basis for the design of a self-propelled system for rice fields, which emphasised the role of the mechanism of interaction with the soil as the primary source of load and wear modes. The study established that the spatial separation of requirements within the part was decisive: areas that worked in bending/torsion required priority in terms of core fatigue endurance, while areas in contact with the soil required stability of the surface layer. This determined the preference for gradient and localised solutions over a “solid” modification of the entire volume. This conclusion was consistent with the development by J. Li *et al.* (2025), where a self-propelled unit for gardens on slopes combined several technological operations and, accordingly, formed nodes of different load characteristics, which reinforced the need for a differentiated approach to strengthening parts of different functional areas. Parallel confirmation was provided by the results of J. Sun *et al.* (2025), where an intelligent self-propelled machine was evaluated through modelling and application, which emphasised the influence of mode controllability on load variability; in terms of the results obtained, this meant that reducing the randomness of modes could keep the system closer to moderate risk zones, while field variability contributed to a transition to combined scenarios.

The study demonstrated that changing the energy and mass concept of a self-propelled machine changed the load profile and, accordingly, the mechanism of component degradation, which made it critical to match the material and reinforcement route to the updated operating conditions. This logic was consistent with the study by L. Xu *et al.* (2025), where the optimisation of a hydrogen-powered self-propelled machine was accompanied by experimental verification, i.e., actual confirmation that design changes require new engineering validation. At the same time, the results of A.K. Roul & D. Singh (2022) on the stability analysis of a self-propelled high-clearance platform emphasised that stability and load mode determine the risk of transition to critical states; in terms of the numerical markers obtained, this demonstrated why a deterioration in stability or an increase in disturbances could shift the system to 4-5 even without changing the material, and therefore required not a “universal” reinforcement, but one adapted to the operating modes. The study determined that reducing the mass and redistributing the stiffness of structures changed the stress concentrations and potentially amplified the fatigue component of degradation, while digitalisation and autonomisation changed the nature of the modes and the variability of loads, affecting the probability of transition to combined scenarios. This approach coincided with the interpretation by Y. Yu *et al.* (2025), where the lightening of the chassis of a self-propelled machine was justified by finite element analysis, i.e., by fixing stress zones directly related to the risks of fatigue damage. A parallel in the study by Q. Liu *et al.* (2025), devoted to autonomous control of agricultural machines, emphasised the growing role of accuracy and repeatability of modes; within the scope of the results obtained, this meant the potential to reduce random load peaks and, accordingly, reduce the probability of entering zone 4-5 by stabilising operating modes.

The study determined that for small farms and prototype solutions, maintainability and resource predictability remained decisive, which made the conceptual model of route selection a reproducible rule. This conclusion was consistent with the study by A. Ghafoor *et al.* (2022), where the development of a prototype self-propelled sprayer emphasised applied suitability and evaluation, i.e., the need for simple but reliable technical solutions. The study by G. Singh *et al.* (2024) on an ergonomically improved operator’s workplace emphasised that the human factor and control modes affect operational loads; in terms of the patterns obtained, this meant that the unevenness of the modes could amplify the impact-cyclic components and contribute to the transition to

combined scenarios, and therefore required a reserve of fatigue endurance of the core for critical power parts. The study determined that for soil cultivation tools and working edges, the most effective approach was one in which the surface was given a wear-resistant functional layer with control of structure, adhesion and tribological behaviour, since it was the surface that limited the resource in modes of contact with the soil. This conclusion was consistent with the findings of H. Nie *et al.* (2024), where the mechanisms of wear resistance and the role of coating structure were analysed for hard carbide coatings applied by high-speed gas-flame spraying; within the scope of the results obtained, this corresponded to the priority of coating and surfacing solutions for working edges. Additionally, a review by A.S. Malvajerdi (2023) on the wear and coating of soil cultivation tools supported the thesis of multi-factoriality and the need to select coatings taking into account the soil and contact dynamics; in terms of the conclusions reached, this meant that the choice of reinforcement route should be based on the configuration “operating conditions → degradation mechanism → critical zone” rather than on a universal class of technology.

Thus, the results of the study showed that the design of technologies for strengthening tractor and self-propelled machine parts in agricultural conditions should be based on the interrelated influence of mechanical loads, abrasive action of soil, and corrosion and agrochemical activity of the environment, since it is their combination that determines the dominant degradation scenario and requirements for the surface layer and core. A systematic comparison of working areas with technology classes confirmed the conclusions of applied research on the effectiveness of functional coatings and controlled surface modification for soil-contacting elements, where the resource was limited precisely by the stability of the surface layer under conditions of friction and abrasive contact.

## CONCLUSIONS

Thus, the results of the study showed that the design of technologies for strengthening tractor and self-propelled machine parts in agricultural conditions should be based on the interrelated influence of mechanical loads, abrasive action of soil, and corrosion and agrochemical activity of the environment, since it is their combination that determines the dominant degradation scenario and requirements for the surface layer and core. A systematic comparison of working areas with technology classes confirmed the conclusions of applied research on the effectiveness of functional coatings and controlled

surface modification for soil-contacting elements, where the resource was limited precisely by the stability of the surface layer under conditions of friction and abrasive contact.

Identification of the dominant degradation mechanisms confirmed the typical mixture of scenarios for agricultural technology: fatigue exhaustion, abrasive and contact-abrasive wear, and corrosion processes mutually reinforced each other, and as conditions became more severe, there was a gradual shift in priority from volumetric fatigue to surface wear and then to corrosive-abrasive and combined scenarios, which shifted the engineering focus from a “stable core” to a “functional surface layer”. A systematic comparison of technological approaches with groups of parts and working areas proved the absence of universal routes: for elements with a resource limited by cyclic stresses in the cross-section, the priority was volumetric thermal or thermomechanical solutions with core stabilisation; for soil-contact edges – the formation of wear-resistant layers and local methods of increasing hardness without critical deterioration of the base; for areas of high contact stresses – thermochemical or combined surface-volumetric technologies with a combination of a hard surface and a viscous core; for components in wet and agrochemically active environments – protective and barrier coatings or chemical-thermal approaches that ensure chemical stability without loss of mechanical reliability.

The study determined that additive manufacturing and restoration should be treated as a preparatory stage of a combined route for restoring geometry and repair allowance, but the predicted resource was ensured only by the combination of “additive stage – post-processing – targeted strengthening” under conditions of process reproducibility, material compatibility and controlled quality; for critically loaded elements, this scheme had limitations due to the risks of defectiveness and structural variability. The integral conceptual model formalised the cause-and-effect chain “operating conditions → degradation mechanism → critical zone → surface and core requirements → technological route class” and substantiated that in the most severe conditions, only hybrid solutions combining at least two principles are effective, since isolated hardness enhancement or barrier protection alone did not cover the entire spectrum of damage. Prospects for further research are related to validating the model on a range of real parts with reference to field conditions, expanding the compatibility criteria of “material – strengthening – corrosive environment” for corrosive-abrasive scenarios, and developing parameterised matrices for

selecting hybrid routes with industrial repeatability and predictable resource effects.

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## CONFLICT OF INTEREST

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## Проектування технологій зміцнення деталей тракторів і самохідних машин в умовах аграрної експлуатації

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**Анотація.** Метою дослідження було теоретично обґрунтувати відтворюваний інженерний підхід до вибору маршрутів зміцнення з урахуванням переходів між механізмами деградації та просторової неоднорідності вимог у межах деталі. Методологія базується на послідовному перенесенні експлуатаційних умов у причинно-наслідковий ланцюг «умови роботи – механізм деградації – критична зона – вимоги до поверхні й серцевини – клас технологічного рішення» з опорою на міжнародні нормативні вимоги до сталей, параметрів зміцнених шарів, корозійної стійкості та довговічності вузлів. Результати показали, що ризик деградації має пороговий характер: при посиленні одного чинника він зростає помірно й концентрується переважно в зоні 2-3 балів інтегральної шкали, тоді як одночасне підсилення двох і більше чинників переводить систему в зону 4-5 балів через синергію корозійно-абразивних і абразивно-втомних процесів. Виявлено зміну «провідного» механізму від переважно втомного за помірних режимів до домінування поверхневих комбінованих сценаріїв за високих режимів, коли визначальною стає стабільність поверхневого шару та його хімічна стійкість. Обґрунтовано, що універсальних технологій не існує: для деталей із критичною роллю серцевини пріоритетні об'ємні термічні маршрути; для контактних зон із ґрунтом – локальне поверхнєве зміцнення та зносостійкі шари; для контактено-напружених зон – термохімічні рішення; для вологого агрохімічно активного середовища – бар'єрний захист. Показано, що адитивне відновлення доцільне переважно як підготовчий етап із подальшою постобробкою та зміцненням, оскільки ресурс визначає саме зміцнений поверхневий шар. Практична значущість полягає в тому, що узагальнена модель може використовуватися інженерами-конструкторами, технологами та сервісними службами аграрного профілю під час проектування й відновлення деталей тракторів і самохідних машин для вибору класу маршруту зміцнення за співвіднесенням умов експлуатації з домінуючим механізмом деградації та критичною зоною деталі, що знижує ймовірність прискореного зношування

**Ключові слова:** механічні навантаження; деградація; абразивне зношування; поверхневий шар; технологічний маршрут; адитивне виготовлення