

Review

A Comprehensive Review of Improving the Durability Properties of Agricultural Harrow Discs by Atmospheric Plasma Spraying (APS)

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Abstract: This paper presents a comprehensive analysis of recent advancements in the application of thermal spraying techniques to enhance the durability and wear resistance of agricultural machinery components, with a particular focus on disc harrow assemblies. Given the harsh conditions under which tillage tools operate—characterized by abrasive wear, impact stresses, and chemical exposure from various soil types—thermal sprayed coatings have emerged as a viable solution to extend the service life of these components. The study discusses various deposition methods, particularly Atmospheric Plasma Spraying (APS), and evaluates their effectiveness in creating high-performance surface layers that resist wear, corrosion, and mechanical degradation. The review also summarizes experimental and field test results for coatings based on materials such as NiCrBSi, WC-Co-Cr, TiO₂, Al₂O₃, Cr₂O₃, and ceramic–metal composites, highlighting their significant improvements in hardness, friction reduction, and resistance to delamination and oxidation. The paper highlights research using thermal spraying techniques, especially APS for agricultural applications, with emphasis mostly on components intended for soil processing and requiring good resistance to abrasive wear.

Keywords: wear resistance; corrosion resistance; plasma spraying; agriculture; disc harrow



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1. Introduction

The agricultural sector is a crucial component of the economy; hence, scientific progress in this field fosters development and enhances living conditions. The mechanization of agriculture plays a fundamental role in increasing labour productivity, reducing costs, and ensuring stable crop yields under favourable conditions [1].

Modern agriculture relies on a wide range of machinery and attachments, with key soil-working implements including ploughs, harrows, fertilizer spreaders, seeders, and cultivators—each designed to perform specific tasks during the soil preparation and planting process by directly interacting with the soil to ensure optimal growing conditions, as presented in Table 1.

Table 1. Main characteristics of soil-contacting agricultural equipment.

Equipment Type	Function	Soil-Contact Elements	Types
Ploughs	Initial soil cutting and turning	Long blades or shanks	<i>Mouldboard Ploughs:</i> Wing-shaped blades for shallow, thorough soil turning.
			<i>Disc Ploughs:</i> Rows of discs for cutting and turning, suitable for sticky or rocky soil.
			<i>Chisel Ploughs:</i> Long shanks for deep tillage (up to 1 foot or more).
Harrows	Soil agitation and surface levelling after ploughing	Teeth, discs, rollers, or chains with spikes.	<i>Spring Harrows:</i> Iron teeth for loosening soil.
			<i>Roller Harrows:</i> Spiked rollers to crush soil clumps.
			<i>Chain Harrows:</i> Chain nets with spikes for aerating and spreading.
Fertilizer Spreaders	Even distribution of fertilizers	Indirect contact via spreading material on soil surface	<i>Disc Harrows:</i> Discs for aggressive soil and weed breakup.
			<i>Broadcast Spreaders:</i> Use gravity for dispersion.
			<i>Manure Spreaders:</i> Spread solid manure; often followed by harrowing.
Seeders	Planting seeds into soil	Drills, blades, or openers	<i>Slurry Spreaders:</i> Spray liquid manure (slurry) directly onto the soil.
			<i>Broadcast Seeders:</i> Disperse seeds over surface (minimal soil contact).
			<i>Air Seeders:</i> Use compressed air to place seeds (requires suitable soil conditions).
			<i>Box Drill Seeders:</i> Drill into soil and deposit seeds at set depth.
Cultivators	Shallow tillage and weed control	Tines or blades used to stir soil near surface.	<i>Planters:</i> Cut into soil, insert seeds, then close soil.

Maintaining the quality of production, operation, and repair of agricultural machinery components extends their service lives and significantly contributes to the efficiency of technological processes in agriculture. Enhancing the durability of tillage machine components, particularly disc-type implements, is a key challenge in agricultural machinery design [2]. Therefore, the development of new designs, the proposal of innovative structural solutions, and the advancement of sustainable technological processes drive the innovation of modern materials for manufacturing agricultural machinery components. Soil-processing equipment operates under extreme conditions, necessitating special attention to maintaining and enhancing the properties of its components [3].

As observed in the literature [4], the enhancement of abrasive wear resistance and corrosion resistance of disc harrows could be obtained by different methods, one of them

being plasma jet thermal deposition. Due to their exposure to soil during agricultural processing, those parts experience significant abrasive wear [5]. Therefore, improving their mechanical properties to enhance abrasion resistance is essential for increasing their durability [6]. The plasma jet thermal deposition method is also employed to create a protective surface layer, reducing contamination levels during soil processing [4,7].

Numerous studies focused on the extent to which soil type influences the abrasive wear of components, highlighting the need for increased attention to this factor, as further presented in Section 2.2. Research indicates that as the size of sand particles in the soil increases, the wear rate of soil-processing equipment also rises, necessitating materials with superior mechanical properties [6,8,9] in terms of abrasion resistance.

As an example, the traction force of both coated and uncoated tillage equipment components was measured, compared, and reported in numerous studies [10]. Also, wear modelling identified several influencing factors, including tool shape, soil characteristics such as moisture content and texture, and tillage tool performance parameters such as feed rate and working depth [11]. Some studies even suggested that tillage equipment designed for shallow soil penetration requires less pulling force. Figure 1 illustrates various disc harrows that are used in soil cultivation [12].



Figure 1. Different types (geometrical forms) of discs in the disc harrow assembly. (a). Single-action disc harrow. (b) Notched edge with small profile. (c). Double-action disc harrow (d). Notched edge with large profile [4,10].

Since tillage directly impacts crop quality, tillage tools—such as the discs in a disc harrow assembly—must exhibit high resistance to abrasive wear. Additionally, impact resistance is crucial, as soil processing poses a risk of component damage. Beyond the abrasive effects of sand, the presence of impurities, foreign objects, or stones (ballast) can cause significant damage or even complete failure of the discs [13].

The specialized literature describes a wide range of surface deposition methods, including spraying, ion plating, laser deposition, electrochemical deposition, and others. All these techniques have potential applications in agricultural equipment and share the common objective of creating a high-performance surface layer. The thickness of the

deposited layers can vary from as little as 4 μm to over 5000 μm , depending on the selected deposition method [14–16]

Table 2 presents examples of key thermal coating methods with potential applications in the agricultural sector, highlighting both the raw materials that can be used and the approximate thicknesses achieved after deposition.

Table 2. Main superficial deposition methods applicable to agricultural equipment, along with examples of raw materials used and approximate thicknesses of the deposited layer [14–16].

Process	Material	Coating Thickness [μm]	Applications/Equipment/ Tillage Tool
Thermal spray/ plasma spray (APS)	WC-Co-Cr, $\text{Cr}_3\text{C}_2\text{NiCr}$, Stellite-21	100–150	Rotavator blades/ harrow disc cultivator sweeps
	Ferrous/Non-Ferrous Alloys, Carbides, Ceramics	400–2500, 50–500, 150–800, 100–200	
High-velocity oxy-fuel flame (HVOF)	25% (Cr_3C_2 -25(Ni20Cr)) + NiCrAlY , Ferrous Alloys, Non-Ferrous Alloys, Self-Fluxing Alloys, Carbides, Ceramics	–, 50–2500, 50–2500, 50–2500, 50–5000, 250–2000	Rotary tiller blades
Electric arc surfacing	Ferrous Alloys, Non-Ferrous Alloys, Unalloyed Cast Iron	100–2500, 100–2500, 100–5000	Rotary tiller blades/ploughshares
Electro deposition	Nanocoatings (Hydrophobic + Ceramic Coating Spray), Nickel chrome plating	200, strat multistrat	Chisel blade
Thermal diffusion	Carbonitriding	140–470	Ploughshares

This work aimed to review the latest research in the agricultural sector that integrates thermal deposition techniques as an efficient method for improving material properties while simultaneously facilitating reconditioning processes.

2. Main Stresses Encountered on Discs and Other Agricultural Components

2.1. Stresses on Disc Harrows in Agriculture

Disc harrows are indispensable tools in modern agriculture, used for soil preparation, breaking up clods, incorporating organic matter, and improving soil aeration [17]. The literature contains research focused on enhancing the durability of rotary tiller blades, addressing the significant wear they undergo in abrasive environments, particularly in dry, sandy soil [5,18]. A rotary tiller is a mechanized agricultural tool widely used to enhance efficiency in soil preparation by reducing labour, fuel consumption, and time. However, tiller blades undergo extreme surface wear, which drastically limits their service life, directly influenced by the wear rate in g/acre. This study aimed to enhance the durability of tiller blades to reduce downtime associated with frequent replacements during operation. Since replacing components is a time-intensive process, utilizing more durable parts results in fewer frequent replacements, thereby optimizing efficiency and minimizing maintenance interruptions. The approach involved hardfacing, examining its impact on wear intensity and wear characteristics of the blades. The impact of chromium surface coatings was assessed by applying a hard finish to the leading edge of high-strength steel tiller blades using gas tungsten arc welding, employing four distinct electrode

types. A comparative analysis was performed on coated and standard (uncoated) blade material through field and laboratory testing to evaluate their wear resistance and durability. The field test was conducted on a 50-acre rice field post-harvest, where the soil was dry and sandy, with rice stubble present. Test blades were strategically positioned within the tiller to gather relevant data. Results indicated that the average wear rate for the uncoated blade was 7.08 g/acre, whereas the coated blades, treated with 5HCr, 7.5HCr, 12HCr, and 8HCr hardfacing layers, exhibited lower wear rates of 5.02 g/acre, 4.3 g/acre, 2.84 g/acre, and 4.22 g/acre, respectively. These findings demonstrated a significant improvement in wear resistance provided by hardfacing treatments compared to the uncoated blade [18]. However, the mechanical stresses they withstand have a significant impact on their lifespan and overall efficiency. The primary factors affecting disc harrows are abrasive wear and impact stresses. Understanding these stresses and implementing effective solutions to mitigate their effects is essential for enhancing the durability and performance of agricultural machinery.

2.2. Abrasive Wear in Disc Harrows

Abrasive wear occurs when hard particles, such as sand, grit, and minerals in the soil, continuously rub against the surface of the harrow discs, leading to progressive material loss [19]. This wear is influenced by several factors, including soil composition, moisture levels, pH, contact pressure, and operating speed [20,21]. The type of soil is a crucial factor in determining the extent of abrasive wear; thus, it is of great importance to have fundamental knowledge regarding it, as presented in Table 3.

Table 3. Main types of agricultural soils of Europe [22–24].

Mechanical Properties	Texture/Granulometry	Hard Materials/Rocks	Usage	Crops
Cambisols (26.7% of Europe's surface) pH: Eutric: >5.5, Dystric: <5.5				
Moderate to deep profiles, weakly developed cambic horizon, stable structure, some erosion risk on slopes	Loamy to clayey; fertile; erosion-sensitive if sloped	Some subtypes (e.g., calcareous) have carbonate nodules; vertic types may swell/shrink significantly	Highly productive for food and oil crops; Mediterranean crops like olives, figs, grapes are also supported	Cereals, oil crops, vines, olives, figs
Luvisols (15% of Europe's surface) pH: Dystric: <5.5, Eutric/Calcic: >6				
Strong textural differentiation with clay-rich argic horizon; good porosity	Medium to fine; clay-rich subsurface can hinder water	Calcic/ferric luvisols may have hardpans; they can affect deep ploughing	Used for mixed and intensive agriculture	Cereals, potatoes, beets, fodder crops
Chernozems (~3.4% of Europe's surface) pH: 6.5–8.5 (neutral to alkaline)				
Deep, stable structure with granular aggregates; very good natural structure	Loamy to clay-rich; deep and nutrient-rich	Few hard materials, high organic content supports easy cultivation	Extensively used for cereals; very fertile steppe soils	Wheat, maize, sunflower
Fluvisols (~3.1% of Europe's surface) pH: variable (often neutral to slightly alkaline)				
Young, stratified; good tilth in floodplain zones; variability due to deposition	Alluvial, fine- to medium-textured; sometimes stratified	Some areas with gravel or recent sediments; variability exists	Floodplain farming; rice, cereals, vegetables	Rice, vegetables, maize, cereals

Table 3. Cont.

Mechanical Properties	Texture/Granulometry	Hard Materials/Rocks	Usage	Crops
Phaeozems (~1.4% of Europe's surface) pH: 5.5–7 (slightly acidic to neutral)				
Well-structured, humus-rich; prone to slight compaction	Loamy to silty; high organic matter improves workability	Minimal rock content; subsoil structure favorable to tillage	Ideal for cereals, sugar beet, vegetables (with irrigation)	Wheat, sugar beet, vegetables
Vertisols (<1.0% of Europe's surface) pH: ~7–8 (neutral to alkaline, varies seasonally)				
Heavy, plastic clays; swell–shrink behavior; difficult tillage when wet	Very clayey; >30% clay; forms cracks in dry season	Slickensides, hard when dry; swelling clays hinder equipment	Cotton, cereals, some pulses; irrigation improves potential	Cotton, wheat, barley

Sandy soils, with their high quartz content, cause more aggressive wear compared to clay or loamy soils [25]. Moisture content also plays a vital role—wet conditions help reduce friction, whereas dry soils exacerbate it, leading to increased material loss. The operating speed of the harrow further influences wear, as higher speeds generate more forceful impacts between soil particles and the disc surface. Additionally, heavier loads create greater downward pressure on the discs, accelerating surface deterioration. The composition of the disc material itself is also a key factor, with harder materials, such as high-alloy steels and high-carbon steels, generally offering greater wear resistance [26,27].

Figure 2 shows both the main types of soil with which agricultural equipment works as well as the influence of these types of soil on the degree of wear of the components.

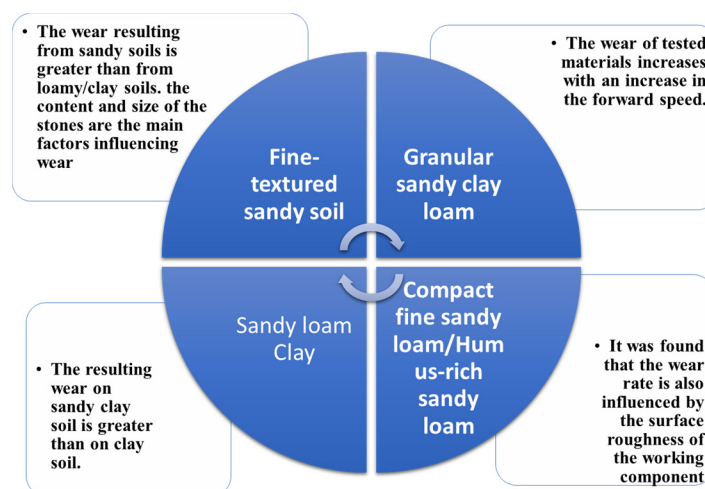


Figure 2. Soil types and influence on the wear of agricultural components [28–32].

As observed, thermal coatings can contribute to the improvement of the resistance to abrasive wear. For a better understanding of this phenomenon, Figure 3 schematically presents the process of abrasive wear of the material during soil processing.

The type of soil plays an important role in the life of the equipment intended for soil processing because the wear rate of these components that come into direct contact with the soil is mainly influenced by the abrasive particles in the soil, as presented in Figure 3. The wear rate of the components is directly proportional to the size of the abrasive particles: the larger they are, the more severe is the wear of the component subjected to soil processing [1,33]. Table 4 presents the distribution of granulometric fractions in cultivated soil, highlighting the proportions of different components such as sand, silt, and clay.

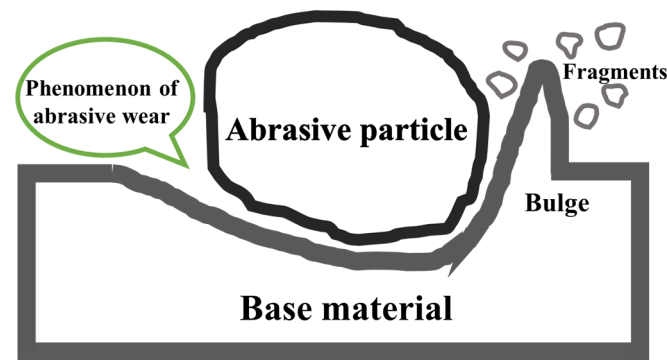


Figure 3. Mechanism of abrasive wear.

Table 4. Typical distribution of granulometric fractions in agricultural soil [34].

No.	Proportion of Granulometric Components by Percentage [%]							Particle Size Distribution in Soil	
	Sand					Silt		Clay	
	Very Coarse $1.0 < d \leq 2.0$	Coarse $0.5 < d \leq 1.0$	Medium $0.25 < d \leq 0.5$	Fine $0.10 < d \leq 0.25$	Very Fine $0.05 < d \leq 0.10$	Coarse $0.02 < d \leq 0.05$	Fine $0.002 < d \leq 0.02$	$d \leq 0.002$	
1	1.9	5.6	12.1	29.1	19.9	11.8	13.7	5.9	fsl
2	2.3	7.0	13.8	26.7	17.0	10.7	16.6	5.9	fsl
3	2.1	5.0	11.1	25.1	15.5	12.7	22.6	5.9	fsl
4	2.1	6.7	17.7	35.2	18.6	7.9	7.9	3.9	fsl
5	1.7	6.0	14.7	31.1	19.0	12.8	10.8	3.9	fsl
6	1.9	5.8	13.7	24.8	23.4	10.8	13.7	5.9	fsl
7	1.7	5.4	14.0	26.2	17.3	12.8	17.7	4.9	fsl

The wear of the components is the main factor that leads both to a lower quality of agricultural works and to high repair and maintenance costs, being followed at the same time by another series of related disadvantages such as energy losses, increased fuel consumption through the need for a greater traction force of the agricultural machine, etc.

2.3. Impact Stresses in Disc Harrows

Impact stresses occur when disc harrows encounter solid obstacles such as rocks, roots, or compacted soil layers. Unlike abrasive wear, which causes gradual material loss, impact stresses can lead to crack propagation, resulting in failure—including cracks, fractures, or permanent deformations. When a rotating disc strikes a hard object, the sudden force generates localized stress concentrations on the surface. Over time, repeated exposure to these forces weakens the material structure, leading to fatigue failure and significantly reducing the optimal operating life of the discs [35,36].

Several factors contribute to impact stresses in disc harrows [37]. The presence of elements found deep below the surface of the earth, such as buried rocks or thick roots, generates sudden and unpredictable forces that compromise the structural integrity of the discs. The speed of operation is another critical factor, as higher speeds amplify impact forces, making the discs more susceptible to cracking or fracturing upon collision. (It is worth mentioning that the average speed is approx. 3.2 km/h^{-1} .) Additionally, the material composition of the disc plays a crucial role: while some materials offer excellent wear resistance, they may also be brittle and more prone to breaking under high-impact loads. Repeated stress cycles, in which the disc experiences continuous shock loading, gradually weaken the material, ultimately leading to failure. Several mitigation strategies were proposed to minimize the negative effects of impact stresses on disc harrows.

One of the most promising solutions is the application of advanced composite coatings, such as Stellite-6/WC applied through laser cladding, which strengthens the disc's microstructure and enhances resistance to sudden shocks [38,39]. Another effective approach

is improving the structural design of the harrow by integrating shock-absorbing mounts and reinforcing high-stress areas to better distribute impact forces. Material selection is also critical—certain alloys, such as boron steel, provide an optimal balance between hardness and flexibility, ensuring durability without excessive brittleness [40].

3. Improving the Properties of Agricultural Component Materials Through Thermal Deposition Techniques

3.1. Evaluation of Coating Properties

The plasma jet thermal coating technique is used to create a high-performance surface layer with a uniform thickness of approximately 100 μm . During the deposition process, several parameters must be carefully considered, including the spraying distance, plasma gas temperature, and the characteristics of the base material, to prevent the risk of delamination or exfoliation of the superficial layer after deposition. Therefore, the material used for surface deposition must be able to withstand these extreme thermal conditions without deforming or reaching its melting point [41,42]. All these main parameters must be taken into account before any deposition to ensure the creation of a stable superficial layer that adheres well to the surface of the base material. At the same time, the substrate can be preheated (usually between 300 and 800 $^{\circ}\text{C}$) to avoid thermal shocks; also, for a much better bond between the deposition material and the base material, intermediate coatings are made to increase the bond [43–45]. Of course, not just any type of thermal spray coating can successfully withstand the demands to which agricultural soil-processing parts are exposed. For these reasons, it is necessary to test them, both in terms of the improvement of their physical and mechanical properties and also in real-life tests.

Figure 4 illustrates the steps involved in evaluating the properties of surface layers produced by thermal spraying on the agricultural components. These tests are essential, as the discs in the disc harrow assembly are exposed to abrasive wear, moisture, and various chemical agents present in the soil, as previously presented.

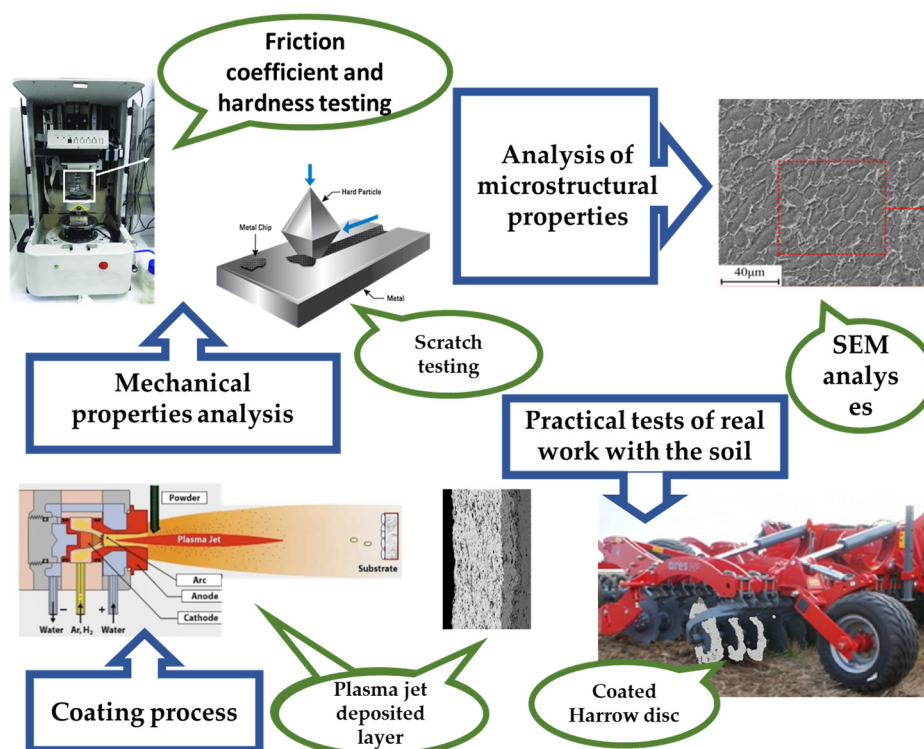


Figure 4. The stages of evaluating the properties from the realization of the coatings and testing in the laboratory to the practical tests of working with the soil.

3.2. Materials Used in the Manufacture of Agricultural Components

Abrasive wear is the main factor of interest when it comes to the life of disc harrow discs. The materials used to manufacture these discs must, first of all, have good resistance to abrasive wear and corrosion. These properties are required because the working environment is an aggressive one, which subjects the discs to use in different types of soil (see Tables 3 and 4 and Figure 2).

According to the specialized literature [46,47], there are several types of materials used in the construction of agricultural components, such as harrow discs, knives, etc., each having a specific chemical composition and distinct mechanical properties, as presented in Table 5.

Table 5. Classification of materials used in soil-contacting agricultural equipment.

Material Type	Common Applications	Properties
High-Carbon Steel	Ploughshares, cultivator tines, harrow discs	Offers good hardness and wear resistance; cost-effective; commonly used in various tools.
Boron Steel	Harrow discs, plough blades	Enhanced hardness (48–52 HRC); improved wear resistance; suitable for heavy-duty use.
65Mn Spring Steel	Disc blades, tines	High elasticity and toughness; maintains shape under stress; hardness around 38–45 HRC.
Alloy Steels	Various soil-engaging components	Tailored properties for specific applications; may include elements like chromium or nickel for added strength and corrosion resistance.
Low-Alloy Steels	General-purpose tillage tools	Balanced strength and toughness; cost-effective for moderate wear conditions.
HARDOX Steel	Various implements	Wear-resistant steel components (HARDOX 400/450/500/600); high hardness and toughness; suitable for demanding applications.
Cast Iron	Components requiring high compressive strength	Good wear resistance; brittle nature; used in parts where tensile strength is less critical.
High-Manganese Steel	Wear plates, crusher jaws	High impact strength and resistance to abrasion once in its work-hardened state.
High-Chromium Alloys	Wear-resistant parts	Excellent hardness and corrosion resistance; used in environments with high abrasive wear.
Cemented Carbides (e.g., WC)	Cutting tools, inserts	Extremely hard and wear-resistant; suitable for high-speed applications; more brittle and expensive.

Table 5. Cont.

Material Type	Common Applications	Properties
Tool Steels (e.g., AISI D2)	Dies, cutting tools	High hardness and wear resistance; maintain a sharp edge; used in precision tools.
High-Speed Steels (HSS)	Cutting tools, drill bits	Maintain hardness at high temperatures; suitable for high-speed machining.
Ceramic Composites	Plough heads, harrow points	High hardness and wear resistance; brittle; used in specialized applications requiring minimal wear.
Surface Coatings (e.g., TiAlN, CrN)	Various tools	Applied to enhance surface hardness and wear resistance; extend tool life without altering base material properties.

We list several particular examples below [48]:

- ✓ **Ploughshares A/1 and A/2:** with base material that contains a high percentage of Mn (1.300%) and Cr (0.342%), which enhances hardness and wear resistance. Other elements include iron (Fe–balance), Ni, Mo, V, and Cu, contributing to durability and toughness. The measured hardness (HV1) is 433, indicating good resistance to mechanical stress.
- ✓ **Cemented Carbide Plates:** are predominantly composed of WC (79.79%) and cobalt (Co–15.67%), which provide high hardness and superior wear resistance. The measured HV30 hardness for these plates is 986, highlighting their capability to withstand extreme operating conditions.
- ✓ **Surface Welding:** has a chemical composition of the welded surface characterized by a significant presence of carbon (4.320%) and Cr (16.790%), ensuring superior abrasion and corrosion resistance. The presence of Nb (3.920%) aids in forming stable carbides, increasing material durability. Iron is present as the base element (Fe–balance), along with other components such as Mn, Si, V, and Al.
- ✓ **Filling Weld (Ploughshare A/2 Weld Beads):** contains Cr (14.160%) and Nb (3.350%) in significant proportions, ensuring a combination of hardness and wear resistance. Carbon content is 3.670%, with additional elements such as Mn, Si, and Cu contributing to optimized mechanical properties.
- ✓ **Knives:** the base material of knives contains carbon (0.392%) and manganese (1.450%), ensuring a balance between hardness and toughness. The measured HV1 hardness for this material is 531. The cemented carbide plates used in knives are predominantly composed of tungsten carbide (WC–85.65%) and cobalt (Co–14.35%), providing high wear resistance. The measured HV30 hardness is 1057, indicating superior performance in demanding applications.

In order to increase the resistance to abrasive wear and corrosion of various types of agricultural equipment, Keyang et al. [49] produced superficial layers of Fe–Mo (Fe–15Mo) on a 65Mn steel substrate, specially intended for the construction of agricultural components. Research was conducted to evaluate microstructural and corrosion resistance, as well as mechanical properties, specifically focusing on resistance to abrasive wear and impact. Following the evaluation of these characteristics, it was determined that the hardness increased twofold, reaching approximately 850 HV, with significantly enhanced wear resistance, compared to the average microhardness of 450 HV.

Another approach by Xuewei et al. involved coatings made of high-entropy amorphous alloys (HEAA) CoNiCrMoNb(BSi), considering the deposition system power (kW). The results showed that the sprayed coating consisted of an amorphous phase and a minor FCC phase. A higher amorphous content was achieved at increased spraying power, leading to improvements in hardness and wear resistance. However, the coating porosity worsened when power levels were either insufficient or excessive, which deteriorated the mechanical and tribological properties of these coatings. The spraying power was optimized at 45 kW to provide higher amorphous content and reduced porosity, resulting in improved hardness and enhanced wear resistance [50–52].

3.3. Improvement of Abrasive Wear Properties Through Thermal Spraying Techniques on Agricultural Equipment

Abrasive wear significantly affects the performance and durability of agricultural equipment, making it essential to enhance material properties and extend component lifespan. Grain et al. [53] researched the increase in wear resistance by applying plasma jet thermal coatings based on NiCrBSi with nanodiamond reinforcement. As a result, a series of benefits brought to the material were found: NiCrBSi-based deposition led to a hardness of approximately 26% by adding a minimum of 2% nanodiamond particles. Values obtained for the microhardness of the plasma-sprayed coatings were 851.5 HV for NiCrBSi, 946.2 HV for NiCrBSi-1ND, and 1076.8 HV for NiCrBSi-2ND.

The NiCrBSi-2% nanodiamond coating significantly improved tribological performance, reducing the friction coefficient by approximately 85% and wear volume loss by about 64% at 873 K, compared to pure NiCrBSi. Tribological tests evaluated the friction coefficient across different temperatures—473 K, 673 K, and 873 K. For NiCrBSi, the friction coefficient was recorded at 0.44 ± 0.02 , 0.35 ± 0.02 , and 0.28 ± 0.04 at these respective temperatures. The NiCrBSi-1ND coating exhibited lower values, measuring 0.33 ± 0.03 , 0.31 ± 0.02 , and 0.09 ± 0.02 . The NiCrBSi-2ND formulation demonstrated the most significant reduction, with friction coefficient values of 0.31 ± 0.02 , 0.26 ± 0.02 , and 0.04 ± 0.03 at 473 K, 673 K, and 873 K, respectively.

- The coatings with nanodiamond led to a significant improvement of the wear resistance of the coatings, forming a continuous and stable layer on the surface of the base material.

It can be appreciated that making NiCrBSi-based coatings leads to a satisfactory increase in wear resistance, which is an important aspect regarding the operating regimes of agricultural equipment. In this regard, future practical research on real-world work with the soil of agricultural equipment can establish exactly the extent to which these deposits truly represent an efficient solution.

A study very similar to the research presented in this paper on the evaluation of the properties of disc harrows was carried out by Joseph et al. [54] on the performance of the soil-processing blades of agricultural motor cultivators. In this work, the superficial coatings based on FeCrMoCBWNb were made using the electric arc deposition technique, a technique that is similar to plasma jet thermal deposition but has a different operating principle. This technique helps us to include another type of method to refer to. The base material used for the deposits was 65Mn, a familiar material used for the manufacture of soil-processing elements such as blades, discs, knives, chisels, etc. The main causes that lead to the operational failure of cultivators' blades are the resistance to abrasive wear and delamination. In this research, the average thickness of the coatings was approximately 460 μm , with a porosity of 1.5–0.49%. According to the tests carried out, the presence of the coating reduced resistance to frictional wear by approximately 53% for 950 t/min (sliding speeds in times per minute) and 8N (applied load). It was found that the wear rate

increased proportionally with the load and efforts occurring during friction and the main wear mechanisms were represented by delamination, abrasive, and oxidative wear.

In Figure 5, both the coating process and tested parts of the tiller blades are schematically presented: (a) types of blades for soil cultivation, (b) the electric arc deposition process, (c) the tiller blades used in this study, (d,e) testing of wear properties, and (f) the tiller on which the blades are subjected to work.

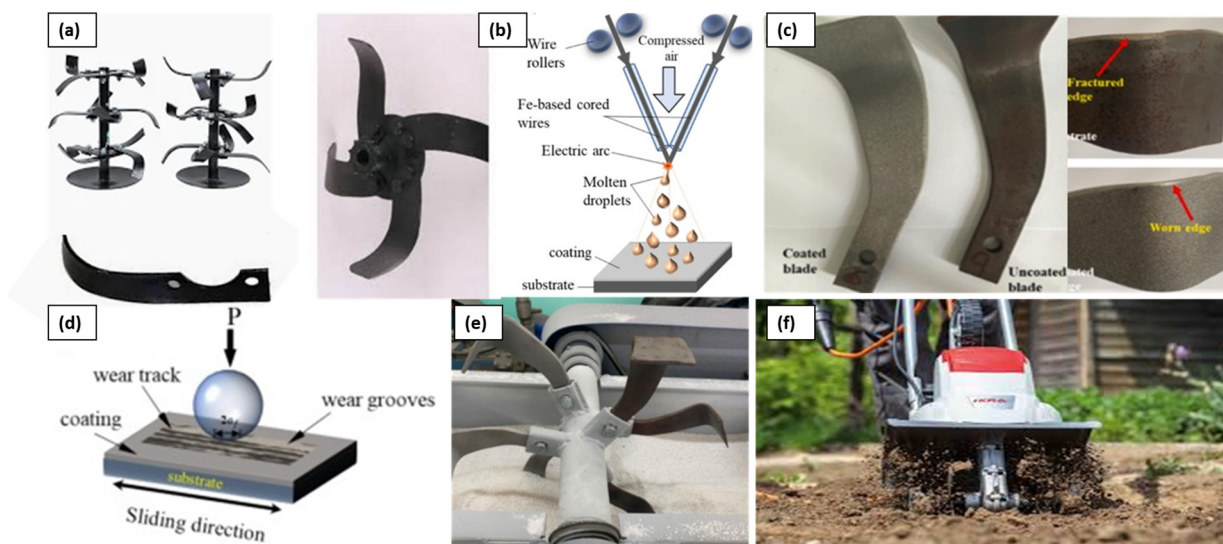


Figure 5. Different types of agricultural parts, coating, and testing processes [54].

The application of Fe-based coatings significantly improves the abrasive wear resistance of tiller blades. They exhibit a longer service life compared to uncoated blades, ultimately improving the working efficiency and durability of tillers.

Another improvement of the agricultural components could be obtained with the help of boron, according to the field tests, which showed that boron steel discs have a significantly longer lifespan compared to traditional steel discs. Research indicated that boron steel discs can last up to 30% longer than uncoated variants. Its presence in steel enhances toughness while maintaining the necessary hardness for efficient soil penetration [55]. Laboratory simulations using ASTM G65 wear testing demonstrated that advanced coatings can reduce wear rates by up to 50%. These tests highlighted the effectiveness of coatings such as NiCrBSi in protecting the underlying metal from abrasive soil particles. Farmers who adopted High-Velocity Oxy-Fuel (HVOF) coatings on their disc harrows reported extended equipment life and reduced maintenance costs. By enhancing wear resistance and reducing the frequency of replacements, coated discs provide a cost-effective solution for modern agriculture. However, further research is necessary to determine the optimal coating for these applications [56].

Wear resistance is the key factor influencing the lifespan of agricultural equipment exposed to soil-working conditions [57–60]. To enhance these properties, Dariusz et al. [61] investigated the effectiveness of composite coatings in extending the service life of agricultural equipment components. In his study, Stellite-6/WC-based coatings were applied via laser cladding to evaluate the improvement in wear resistance under extreme operating conditions for agricultural equipment components that come into direct contact with soil. Experimental analyses demonstrated an increase in hardness from approx. 400–430 HV0.1 to 450–600 HV0.1. Based on the 140 ha of land worked during the agricultural equipment tests, these higher hardness values led to an additional working capacity of up to 30 ha. These enhanced performances were attributed to the presence of hard phases in the coating material (WC, W_2C , M_7C_3 , and $M_{23}C_6$).

The laser-cladding technique proved to be highly effective for this application, as it produced coatings with excellent mechanical properties. One notable drawback, however, was the higher porosity of the coatings. Nevertheless, considering agricultural applications—particularly in soil-working equipment—this does not necessarily represent a major disadvantage. It is worth mentioning that before any benefit is brought by creating coatings, apart from the technical aspects, a decisive factor is also the costs: on the one hand, the costs of raw materials, and, on the other, the high costs of acquiring deposition installations.

Figure 6 presents the advantages and disadvantages of coatings obtained by the laser-cladding technique.

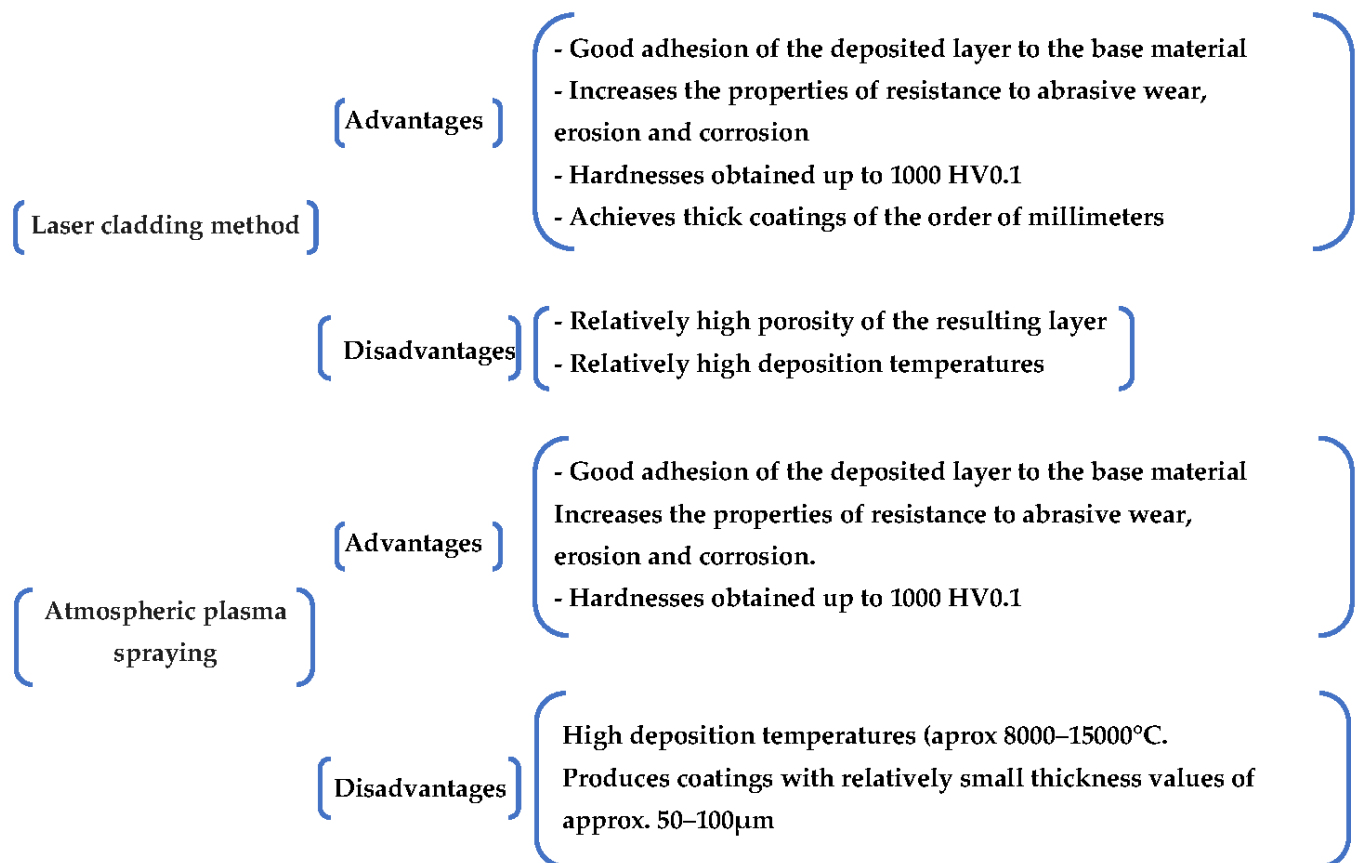


Figure 6. Schematic view of the main findings from the laser deposition of agricultural components in this work [61].

Agricultural tools operate in highly abrasive environments, where continuous friction with soil particles leads to gradual degradation. Soil properties, such as composition, pH, and moisture content, play a significant role in influencing wear rates. It is worth mentioning that there may also be certain areas not specifically intended for agricultural crops, where the presence of quartz sand and corundum grains, both highly abrasive materials, leads to an even greater acceleration of material loss. Two studies [62,63] highlighted the challenges in predicting and controlling tool wear in soil environments, emphasizing the need for experimental research and artificial neural network modelling. The authors discussed how wear tests conducted in natural soil conditions, along with laboratory simulations using controlled abrasive materials, provided valuable insights into the mechanisms of tool degradation.

Microscopic observations confirmed that the coatings were free of cracks, porosity, and surface defects, indicating excellent bonding between the coating and the substrate. The

laser-cladding process resulted in a uniform microstructure, with tungsten carbide (WC) particles embedded within a cobalt-based Stellite-6 matrix. X-ray diffraction (XRD) analysis identified the presence of WC, W_2C , M_7C_3 , and $M_{23}C_6$ phases, all of which contribute to enhanced hardness and wear resistance. The study also revealed that WC particle distribution was denser near the surface, further improving resistance to abrasive wear. Microhardness tests demonstrated a significant increase in hardness due to the incorporation of tungsten carbide (WC) particles. While pure Stellite-6 coatings typically exhibit hardness values ranging from 450 to 600 HV0.1, the Stellite-6/WC composite coatings achieved surface hardness values of approximately 1650 HV0.1—representing a fourfold increase compared to the B27 boron steel substrate. The study found that hardness values were highest at the surface, with a gradual decrease toward the substrate (the hardness increased from approx. 400 HV for the substrate to approx. 1600 HV for the coating layer, this increase being due to the addition of tungsten carbide particles). This hardness gradient plays a crucial role in enhancing impact resistance and preventing brittle failure. The wear resistance of the coated tools was evaluated under real agricultural conditions. Field tests were conducted using coulters installed on a Horsch Terrano 6FG cultivator, which operated in high-humidity soil conditions. The coated tools were directly compared against uncoated commercial coulters, with both sets mounted on the cultivator for an objective evaluation. The assessment involved mass loss measurements taken before and after field operation, along with optical scanning using a GOM ATOS II scanner to analyse geometric changes. The results indicated that the coated tools exhibited 25% greater durability compared to their uncoated counterparts, demonstrating the effectiveness of Stellite-6/WC coatings in extending the lifespan of agricultural implements. The results of the mass loss measurement after continuous operation in soil are shown in Figure 7 [61,64,65].

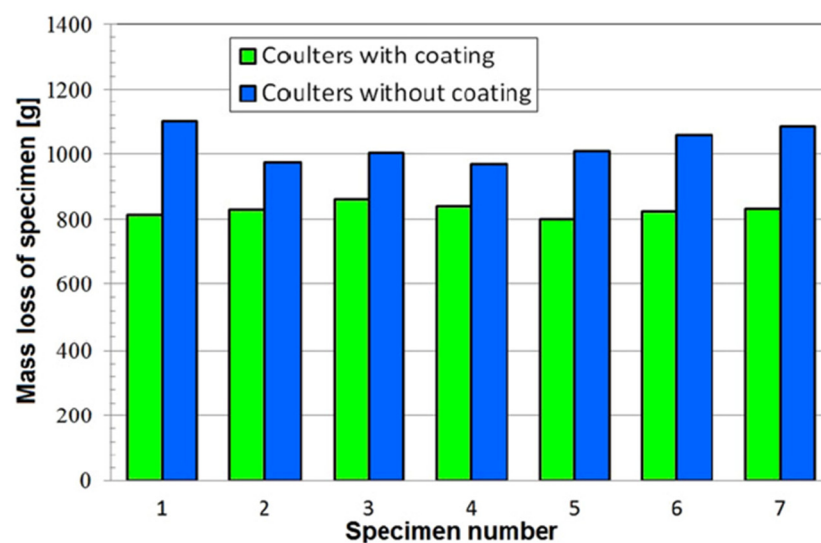


Figure 7. Results of mass loss measurement after continuous operation in soil over an area of 140 ha: green indicates tools with Stellite-6/WC coating, blue indicates tools without coating [61].

The successful application of laser-cladded Stellite-6/WC coatings presents a promising solution for extending the operational lifespan of soil-engaging tools. This advancement ultimately benefits farmers by reducing downtime and increasing efficiency in soil cultivation processes.

This study makes a valuable contribution to the field of agricultural tool durability enhancement, demonstrating that advanced coatings can significantly improve wear resistance and lower equipment maintenance costs.

3.4. Performance Evaluation on Plasma-Sprayed Coatings with Enhanced Mechanical Properties for Agricultural Soil Processing

In the context of modern agriculture, increasing the durability and efficiency of the machinery is a major strategic objective. Components subject to direct soil tillage—such as tillage knives, cutters, tillers, cultivators, discs, or harrow working parts—face extreme stresses on a daily basis: intense abrasive wear in dry environments, repeated impacts, chemical corrosion caused by soil moisture or fertilizers, and high thermal variability. These conditions favour the accelerated degradation of metal components, with direct effects on maintenance costs, equipment availability, and crop yields.

In this context, Atmospheric Plasma Spraying is emerging as a leading technology to improve the performance of these components. This method can be used to coat dense, highly adherent layers of ceramic, metallic, or ceramo-metallic materials with controllable microstructure and outstanding resistance to dry abrasive wear—the dominant demand in agricultural tillage. Table 6 briefly presents a selection of literature studies of plasma-sprayed coatings targeting precisely the mechanical and tribological properties required for applications similar to those in the agricultural industry, especially in the soil-processing sector. More details regarding the techniques and parameters used for tribological characterization of the APS coatings are presented in Appendix A.

Table 6. Literature survey on plasma-spray coatings with tribological characteristics.

Ref.	Coating Material	Results and Discussions
[66]	Fe-based metallic glass (FeW-CrNiMoBSiC)	✓ The coating produced at 40 kW had the most compact structure, highest crystallinity, and greatest hardness, yet the 30 kW coating achieved the highest amorphous content. ✓ All coatings had similar friction coefficients (0.8–0.9), but their wear resistance varied. The 35 kW coating exhibited the lowest wear rate, highlighting that optimal wear resistance depends not solely on hardness but on a balance among hardness, toughness, and resistance to abrasive wear.
[67]	AlCoCrFeNi HEA with Ag + BaF ₂ /CaF ₂	✓ All sprayed coatings displayed dense, lamellar structures with minimal defects, and Ag and BaF₂/CaF₂ phases were stably retained in the HEA matrix. ✓ For the pure HEA (H0), both the coefficient of friction (COF) and wear rate decreased with temperature due to a transition from abrasive to oxidative and delamination wear. The H3 coating (Ag and BaF₂/CaF₂) showed a tenfold reduction in wear rate at room temperature, where delamination from crack propagation was the main wear mechanism, indicating enhanced resistance to abrasion.
[68]	Ni60 alloy	✓ As spraying power increased, coating porosity decreased from 1.58% to 0.97%, resulting in a denser microstructure without cracks, that contained Cr₇C₃, Cr₂₃C₆, and Ni₃Fe phases. ✓ Microhardness peaked at 806 HV_{0.1} at 45 kW, then slightly declined. Lower chromium content contributed to more stable hardness. Under stable wear conditions, the coefficient of friction rose with load, but the 45 kW coating showed the best wear resistance and minimal material loss. Higher loads led to larger wear scars and increased wear volume.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[69]	Cr ₂ O ₃ –65%TiO ₂ (CT65)	✓ The increase in H₂ flow rate (from 4 to 8 L/min) significantly improved the tribological performance of Cr₂O₃–65%TiO₂ coating: the average COF decreased from 0.36 to 0.31, and the wear rate was reduced by 81.8%. ✓ The microstructure became denser, the particle bonding and the coating cohesion were improved, facilitating the formation of stable friction films. Thus, the wear mechanisms transitioned from predominantly abrasive (lower H₂ flow) to more adhesive at higher flow rates.
[70]	Fe-based amorphous/nanocrystalline (Fe ₆₃ Cr ₉ P ₅ B ₁₆ C ₇)	✓ Under low loads, deformation occurred via ploughing and plastic flow, while higher loads caused fracture and chipping. At dry sliding wear tests, the main wear mechanisms were fatigue, abrasion, and oxidation, increased by the presence of oxidation and debris-induced third-body abrasion. ✓ The coating has high hardness (~10.5 GPa), good plasticity index (H/Er = 0.073), and high elastic recovery (~55%). ✓ Friction behaviour varied with load: under constant loading, friction increased with load, whereas under ramped loading, friction remained more stable, highlighting the advantages of strain rate control in improving tribological stability.
[71]	Al ₂ O ₃ /ZrO ₂ ceramic + epoxy + PFPE	✓ The hybrid Al₂O₃ coating + epoxy resin + PFPE showed excellent tribological performance. It achieved an 80.5% reduction in friction (COF down to 0.15) and a drastic drop in wear rate due to the formation of a durable, self-healing lubricating film. This film was produced during sliding, integrated wear debris, and minimized abrasive wear, making the coating ideal for high-load, dry-contact applications requiring both strength and lubrication.
[72]	MoS ₂ with 2–4% CNTs	✓ The 2 wt% CNT-reinforced MoS₂ coating (M2C) showed excellent tribological performance, with low COF (0.07) and significantly reduced wear due to the formation of a durable tribo-chemical film. ✓ The synergistic interaction between CNTs (as nano-bearings) and MoS₂ layers (for easy shear) enhanced lubrication and wear resistance. In contrast, excessive CNTs (M4C) led to agglomeration, increasing friction and wear. M2C demonstrated the best balance of mechanical strength and tribological efficiency, making it ideal for industrial wear-resistant applications.
[73]	NiCrAlY with 0, 3, 6, 12, 18 wt% Al ₂ O ₃	✓ The addition of Al₂O₃ reduced the wear rate significantly—from 5×10^{-4} to 5×10^{-6} mm³/Nm—by shifting the dominant wear mechanism from adhesive and delaminative wear to tribo-oxidation. Although the Al₂O₃ addition had a limited effect on hardness, it played a key role in reducing wear and improving the coating's resistance to sliding contact. ✓ The transition of dominant wear mechanism was driven by the fragmentation and pull-out of Al₂O₃ particles, which helped form a protective tribo-layer.
[74]	Al ₂ O ₃ /PFA base with PFPE oil	✓ The composite coating showed excellent tribological performance due to its self-lubricating design. Using coating porosity as reservoirs for PFPE, it achieved an 82% reduction in friction (COF as low as 0.07) and up to 99% lower wear rates. ✓ This was enabled by protrusion structures at the sliding interface that trapped debris and sustained a lubricating film. As PFPE depletes, these structures degrade, leading to increased friction and wear, marking the end of the coating's effective lifespan.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[75]	Ni-5 wt% Al with Bismuth addition	✓ The coating exhibited temperature-dependent tribological performance. ✓ At 25–200 °C, Bi and δ-Bi₂O₃ reduced friction but caused higher wear due to their softness. ✓ At 400–800 °C, phase transformations and oxidation formed a robust tribo-layer that significantly improved wear resistance and reduced friction. ✓ At 800 °C, had the best performance, where a dense, nanocrystalline tribo-film minimized direct contact. Notably, this tribo-layer showed a “memory effect”, continuing to protect the surface during later low-temperature use.
[76]	Cr ₂ O ₃ with the addition of varying stainless-steel ratios (Fe-Cr-Ni)	✓ The coatings showed improved dry abrasion resistance with higher Cr₂O₃ content due to increased hardness, with pure Cr₂O₃ performing best in this environment. ✓ In slurry abrasion, a balanced mix of 53% Cr₂O₃ and 47% stainless steel provided optimal performance, as pure ceramics were more prone to particle detachment. ✓ Tailoring the ceramic–metal ratio is very important, based on the expected wear type: high ceramic content for dry abrasion, and balanced cermet composition for slurry conditions.
[77]	Cu-15Ni-8Sn spinodal alloy	✓ Aging treatment significantly enhanced the tribological performance of plasma-sprayed Cu-15Ni-8Sn coatings. While as-sprayed coatings suffered from delamination and particle spallation, aging improved cohesion and reduced wear. ✓ Aged coatings had 3–4 times lower wear rates than as-sprayed ones, based on the formation of a stable tribo-layer during sliding. The main wear mechanism shifted to tribo-layer fatigue delamination, making them well-suited for wear-resistant applications after post-treatment.
[78]	NiCrBSi-Zr (with ZrH ₂), compared to pure NiCrBSi	✓ Despite slightly lower hardness, NiCrBSi-Zr offered better wear resistance, lower friction, and less spalling (due to its dense microstructure and strong inter-splat bonding) compared to the standard NiCrBSi. It maintained stable friction (against GCr15 steel) and formed effective transfer layers that reduced wear. ✓ These results highlight the role of cohesive strength and microstructural stability in enhancing the wear performance of Zr-modified coatings.
[79]	WS ₂ and Bi ₂ S ₃ solid lubricant coatings	✓ Spray-coated WS₂ coatings demonstrated excellent tribological performance, maintaining a low COF (~0.13–0.15) and forming a stable tribofilm with long-term wear resistance, even at 200 °C. ✓ Bi₂S₃ coatings had higher friction, poorer film stability, and shorter wear life. ✓ Plasma spraying degraded both materials’ lubricating properties due to thermal decomposition, while air spraying preserved their layered structure. Overall, spray-coated WS₂ proved to be a superior solid lubricant for dry, high-temperature applications.
[80]	TiO ₂ –ZnO and TiOx ceramics	✓ TiOx coatings showed superior tribological performance due to their higher hardness and stable oxide tribofilm formation, offering better wear resistance across all temperatures. ✓ TiO₂–ZnO coatings had a lower COF at 25 °C (0.83 vs. 1.05) and suffered from higher wear, especially at 400 °C. At 800 °C, both coatings formed protective films, reducing COF (~0.4), but TiOx maintained better wear resistance. ✓ TiOx coatings performed more reliably under sliding conditions, especially at high temperatures.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[81]	Cr ₂ O ₃	✓ The 650A coating, with denser structure and lower porosity, showed the lowest friction coefficient (0.348) and minimal wear loss. ✓ The 550A coating had more pores, leading to higher friction and abrasive wear. ✓ The current increase enhances microstructure, improving hardness, bonding strength, and wear resistance, making the coatings more suitable for demanding sliding applications.
[82]	AlN (from Al/AlN composite powder)	✓ AlN coating showed excellent tribological performance, with the wear rate reduced by ~87% and the COF lowered from 0.8 to 0.45 compared to pure Al coatings. ✓ Its high hardness and smooth surface contributed to reduced ploughing and grain removal under dry sliding, making it highly suitable for wear-critical applications, especially harsh environments.
[83]	Ytterbium disilicate (YbDS) with variable PE content	✓ Coatings with low porosity exhibited ploughing and high friction, while high-porosity coatings promoted brittle wear and easier material removal, improving abrasability. The optimal tribological performance was achieved with 1.5 wt% PE, balancing erosion resistance and low cutting forces. ✓ This highlights the potential of tailoring porosity depending on PE content to enhance wear behavior and surface interaction in turbine applications.
[84]	WC-based powder	✓ The WC-based coatings significantly improved wear resistance (by ~30%) and reduced the COF from 0.02 to ~0.12. Pin-on-disc tests confirmed lower material loss and better frictional stability. ✓ This enhancement is due to the dense microstructure, strong interfacial bonding, and formation of a hard, protective surface layer, making the APS method highly effective for wear applications.
[85]	Nanostructured and conventional Al ₂ O ₃ 3 wt% TiO ₂	✓ The nanostructured Al₂O₃-3 wt% TiO₂ coating showed 40–60% lower wear rates than the conventional version, despite similar friction coefficients, due to its fine-grained, tough microstructure that suppressed crack propagation and delamination. ✓ At low loads, it presented mainly adhesive and micro-abrasive wear, while at high loads, wear shifted to plastic deformation. An iron oxide tribofilm formed at lower loads, further enhancing protection. ✓ In contrast, the conventional coating suffered brittle fracture and rapid wear, confirming the nanostructured variant's superior tribological performance, especially under cyclic loading.
[86]	Al ₂ O ₃ + 13 wt% TiO ₂ (AT13)	✓ The AT13 coatings realized at shorter spray distances exhibited better wear resistance due to denser microstructures, stronger splat bonding, and reduced delamination. ✓ Longer spray distances led to weaker bonding and more material removal during sliding. ✓ Optimized spray settings enhanced not only microhardness and fracture toughness but also dry sliding wear resistance. The precise control of coating parameters is critical for durable coatings.
[87]	Mo–NiCrFeBSiC	✓ The 7-pass coating (7L) achieved the lowest wear rate and optimal friction stability due to balanced microstructure and moderate surface roughness being the best compromise for wear resistance and mechanical stability under dry sliding conditions in terms of thickness. ✓ The 5L coating wore quickly due to its fragile structure.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[87]	Mo–NiCrFeBSiC	✓ The 9L coating showed increased abrasive wear due to hard particle agglomeration. ✓ MoO₂ formation contributed to solid lubrication, lowering friction across all samples (CoF ~0.3).
[88]	Alumina and alumina-graphite	✓ Al₂O₃-graphite coatings had significantly lower COF (up to 49% reduction) compared to pure Al₂O₃ coatings, thanks to graphite's self-lubricating effect. ✓ In Al₂O₃ coatings, abrasive wear and brittle fracture dominated, while Al₂O₃-graphite coatings exhibited micro-cracking and delamination, influenced by graphite degradation. ✓ Higher torch power improved melting and microstructure compactness, leading to lower wear rates and enhanced splat bonding due to balancing graphite retention and structural densification.
[89]	YSZ, YSZ/Ag, YSZ/MoO ₃ , YSZ/Ag/MoO ₃	✓ Ag reduced friction at low temperatures but lost effectiveness above 200 °C. ✓ MoO₃ provided high-temperature lubrication but had poor wear resistance. ✓ YSZ/Ag/MoO₃ coatings, which formed Ag₂MoO₄ tribo-films above 500 °C, had the best results, ensuring low wear and stable friction across all temperatures. The synergy between Ag and MoO₃ enabled effective lubrication from 25 °C to 800 °C.
[90]	Diamond/Ni–P composite (DMMC)	✓ APS can produce diamond-reinforced Ni–P coatings with excellent wear resistance. Tribological behavior depended on spray parameters, which influenced diamond retention and fragmentation. ✓ Coatings with more retained diamond (NCD-PS2, PS3) formed thicker tribo-films, reducing wear but increasing counter-body abrasion. ✓ NCD-PS1, with larger, fewer diamond particles, showed more brittle fracture and abrasive wear. ✓ Tribo-film formation, embedded diamond particles, and matrix densification were key to the coatings' high wear resistance.
[91]	Al ₂ O ₃ with Ni-5%Al and Bi ₂ O ₃	✓ Addition of Ni-5% Al and Bi₂O₃ to Al₂O₃ coatings, especially with heat treatment, greatly improves tribological performance. ✓ Solid lubricants like NiBi and Bi₂O₃ reduce friction and wear at all temperatures, while a tribo-oxide layer formed at 800 °C provides excellent high-temperature lubrication. ✓ Heat-treated coatings showed the best results, offering lower friction, better toughness, and higher wear resistance despite slightly reduced hardness.
[92]	YSZ	✓ Pairing with Si₃N₄ and GCr15 led to favorable tribo-layer formation, reducing friction and wear—GCr15 even caused material transfer to the coating. ✓ Al₂O₃ and ZrO₂ induced abrasive wear and brittle fracture, increasing wear rates due to irregular debris and high flash temperatures. ✓ Effective tribo-layer formation and temperature control are key to optimizing YSZ's tribological performance, varying with the counterpart material.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[93]	NiMoAl base with Ag and WS ₂ solid lubricants	✓ NiMoAl–Ag–WS₂ coating achieved the lowest friction (down to 0.16 at 800 °C) and wear rates at all temperatures, due to tribo-chemical formation of lubricious oxides and silver molybdates. ✓ Despite a slight drop in hardness, the combined effect of Ag and WS₂ ensured strong lubrication and wear resistance, making the coating ideal for demanding high-temperature applications.
[94]	YSZ reinforced with graphene nanoplatelets	✓ The GNPs reduced the wear rate by ~45% and the COF by ~51% (down to 0.19 at 873 K), thanks to solid lubrication and smoother tribofilm formation. ✓ GNPs also enhanced hardness and reduced abrasive wear, cracking, and delamination, making the coatings ideal for wear-resistant, high-temperature applications on SS316L substrates.
[95]	CoCrNiW and NiCoCrAlYTa/Cu/Mo coatings	✓ CoCrNiW had higher hardness and relied on oxide glaze formation above 600 °C to reduce friction. ✓ NiCoCrAlYTa/Cu/Mo coating, though softer, maintained more stability and lower friction due to self-lubricating oxides like CuO and CuMoO₄. At 800 °C, it achieved the lowest wear rate, making it the superior option for consistent tribological performance at elevated temperatures.
[96]	Metco 32 and Metco 72 powders	✓ Metco 32 offered higher hardness and better wear resistance, ✓ Metco 72 showed lower friction, especially under dry conditions, due to its smoother surface obtained from post-spray surface finishing. ✓ In grease-lubricated tests, all coatings reduced friction, though surface roughness influenced lubrication regimes. No coating failure occurred, confirming their durability.
[97]	Cr ₃ C ₂ -25(Ni20Cr), MgZrO ₃ -35NiCr, ZrO ₂ -5CaO	✓ The ceramic coating (ZrO₂-5CaO) showed the best post-operation durability, likely contributing to reduced wear and maintaining surface integrity under engine operation conditions. ✓ All coatings maintained structural stability without delamination, indicating good wear resistance alongside corrosion protection, making them suitable for prolonging engine component life in harsh environments.
[98]	Al ₂ O ₃ -40TiO ₂ (AMDRY 6250)	✓ Al₂O₃-40TiO₂ coatings reduced surface wear significantly, remained stable under varying loads, and featured a dense, defect-free structure with high hardness. ✓ These properties led to improved durability and lower maintenance needs in water pump environments, confirming their effectiveness for tribologically demanding applications.
[99]	ZrO ₂ -Al ₂ O ₃ (ZAC) and fused ZrO ₂ -Al ₂ O ₃ (FZA)	✓ FZA coatings showed superior tribological performance over ZAC and Al-Si alloy, with lower wear rate and friction coefficient due to stable tribo-oxide layer formation. ✓ They had higher hardness (1247 HV) and smoother surfaces. Optimal performance was achieved at 10 N load and 1.0 m/s, with a CoF of 0.357 and wear rate of 0.75×10^{-4} g/m. ✓ FZA coatings deliver superior tribological performance due to their structural integrity, hardness, and efficient self-lubricating behavior during operation.

Table 6. Cont.

Ref.	Coating Material	Results and Discussions
[100]	Al ₂ O ₃ -xTiO ₂ composite coatings (x = 3, 13, 20, 40)	✓ Al₂O₃-xTiO₂ coatings showed excellent tribological performance due to reduced porosity, improved toughness, and formation of Al₂TiO₅. ✓ AT13 achieved a low CoF (0.27) and over 90% wear reduction compared to the substrate. ✓ Optimized spraying parameters further enhanced wear resistance ($0.16 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$), making these coatings ideal for high-durability industrial applications.
[101]	Al ₂ O ₃ -13% TiO ₂	✓ Al₂O₃-13% TiO₂ (AT13) coatings showed improved tribological performance in wet environments when sprayed at higher arc power. ✓ They had lower friction and wear rates due to better particle melting, reduced porosity, and stronger interlamellar bonding. ✓ Optimal spraying conditions enhanced resistance to ploughing and delamination, making AT13 coatings ideal for components exposed to combined cavitation and wet sliding wear.
[102]	Ceramic (Al ₂ O ₃ -ZrO ₂)-reinforced chromium steel matrix (0–100 wt% ceramic)	✓ APS coatings with 35 wt% ceramic reinforcement (AZC 035) offer the best tribological performance for engine cylinders. The composition minimizes adhesive and fatigue wear, reduces delamination, and enhances oil retention and lubrication. ✓ Pure metallic coatings wore quickly, while high ceramic content ($\geq 50 \text{ wt\%}$) caused brittleness and abrasive damage. ✓ Optimized ceramic content balanced hardness, durability, and friction control, making it ideal for reducing wear in demanding engine conditions.

As can be seen from the examples analysed and summarized in Table 2, there are a multitude of advantages that APS coatings can bring to the soil-processing sector of the agricultural industry when using ceramic or carbide-based powders:

Al₂O₃ (Alumina):

- ✓ Exhibits high hardness and abrasion resistance, especially when nanostructured or reinforced with TiO₂ or lubricants like graphite or PFPE.
- ✓ Enhances wear resistance through dense microstructures that suppress crack propagation.
- ✓ When combined with polymers (e.g., epoxy or PFA), it forms self-healing lubricating films, significantly reducing friction and wear under dry, high-load conditions.
- ✓ Corrosion resistance is improved through low porosity and chemical stability.
- ✓ Shows improved tribological performance under cyclic and sliding loads, especially with added TiO₂ (e.g., AT13 composition).

Cr₂O₃ (Chromia):

- ✓ Offers exceptional wear resistance, particularly in dry abrasive environments due to its high hardness and chemical stability.
- ✓ Performance improves with higher spray current or optimized hydrogen flow, which densifies the microstructure and reduces porosity.
- ✓ Can be blended with metals (e.g., stainless steel) to enhance resistance in slurry abrasion environments.
- ✓ Oxidation resistance and tribofilm stability further support its use in high-temperature or high-load applications.

TiO₂ (Titania):

- ✓ Coatings like TiO_{2-x} or TiO_x offer high hardness and electrical conductivity and form stable oxide films, reducing adhesion and enhancing wear resistance.

- ✓ Tribological performance is improved with post-annealing or electrical current flow, which encourages the formation of protective tribo-oxide layers.
- ✓ TiO_2 – ZnO composites are less effective at high temperatures, while TiO_x remains more stable, offering better thermal wear stability.

ZrO_2 (Zirconia):

- ✓ Provides a dense, crack-free coating with strong interfacial bonding and good surface integrity.
- ✓ Especially suited for biomedical and high-wear applications due to its mechanical stability and low porosity.
- ✓ ZrO_2 – Al_2O_3 composites (e.g., FZAC) show superior tribological behaviour, forming stable tribo-oxide films with low friction and wear rates.
- ✓ Can be tailored for applications requiring oxidation resistance, chemical inertness, and wear durability under cyclic or biomedical loading.

Carbide-Based Coatings (e.g., WC-Co, Cr_3C_2 -NiCr):

- ✓ Deliver superior hardness and abrasion resistance, even under extreme mechanical loads.
- ✓ WC-Co coatings significantly reduce wear (by ~30%) and provide a stable friction coefficient, making them ideal for dry sliding industrial applications.
- ✓ Cr_3C_2 -based coatings offer excellent performance at high temperatures due to their oxidation resistance and ability to form protective surface layers.
- ✓ Effective in reducing material loss, spalling, and delamination, while maintaining structural integrity during rolling contact or impact wear.
- ✓ Suitable for applications requiring a combination of mechanical strength and thermal stability, such as in pump sleeves, valve components, and heavy-duty machinery.

It is clear that the ceramic oxide coatings (Al_2O_3 , Cr_2O_3 , TiO_2 , and ZrO_2) or carbides produced by APS exhibit advanced tribo-mechanical and physico-chemical properties, including enhanced hardness, superior wear and corrosion resistance, and high thermal and oxidative stability, thus offering effective surface engineering solutions for components operating under severe mechanical and environmental stress, including:

- Increased resistance to dry abrasive wear—an essential characteristic in sandy or dry soil-working conditions, where hard particles generate continuous friction on the metallic surfaces.
- High and stable hardness—oxide (Al_2O_3 , Cr_2O_3 , TiO_2)- or carbide-based coatings can achieve hardness values exceeding 1000 HV, maintaining their integrity even under repeated loads.
- Good adhesion to metal substrates—the APS coating process allows a strong mechanical bond to substrates such as alloy steel, which is commonly used in agricultural tool construction.
- Oxidation and corrosion resistance—of relevance in high-humidity environments or contact with agrochemical solutions.
- Adaptability to complex geometries—useful for protecting critical areas of parts in contact with the soil.

4. Conclusions

The agricultural sector is placing increasing emphasis on enhancing the material properties of components used in soil processing. Different thermal coating methods have proven to be highly effective in this industry, significantly extending the lifespan of agricultural machinery components by providing a protective surface layer. Abrasive wear resistance is the primary factor affecting the durability of disc harrow discs, and research

in the specialized literature showed that wear rates can be reduced by up to 84% through advanced coating techniques.

Soil composition plays a crucial role in wear rates, with sandy soils causing higher levels of abrasive wear, particularly as abrasive particle size increases. Given the severe operating conditions faced by disc harrow discs during soil cultivation, thermal coatings contribute to extending their service life by 60%–70% by forming a durable protective layer against wear.

APS coatings demonstrate remarkable potential for agricultural soil-processing tools, due to the following advantages:

- ✓ **superior wear resistance:** *Fe-based amorphous/nanocrystalline coating* exhibited high hardness (~10.5 GPa) and 55% elastic recovery, contributing to excellent wear resistance under dry sliding conditions; *NiCrAlY + Al₂O₃* wear rate dropped from 5×10^{-4} to 5×10^{-6} mm³/Nm with the addition of Al₂O₃—a 100-fold improvement; *Al₂O₃–3 wt%TiO₂ nanostructured coating* achieved 40%–60% lower wear rates compared to conventional counterparts; *WC-based coatings* have improved wear resistance by ~30% over the uncoated AISI 1045 steel;
- ✓ **customizable friction and toughness:** *Cr₂O₃–65%TiO₂ coating*—adjusting hydrogen flow reduced the coefficient of friction from 0.36 to 0.31 and wear rate by 81.8%; *Al₂O₃ + 13 wt% TiO₂ coatings*—customizing spray distance yielded improved fracture toughness and dry sliding resistance, with denser structures and lower delamination; *NiCrBSi–Zr coating* achieved better wear resistance and lower friction, emphasizing tunable toughness through microstructural control;
- ✓ **self-lubricating properties:** *Al₂O₃/ZrO₂ + epoxy + PFPE* achieved an 80.5% reduction in friction (COF to 0.15) and drastically lowered wear due to a self-healing lubricating film; *MoS₂ + 2% CNT* demonstrated CoF of 0.07 with durable tribo-chemical film formation and optimal solid lubricant content minimized wear; *YSZ/Ag/MoO₃ coatings* formed Ag₂MoO₄ tribo-films at high temperatures (≥ 500 °C), maintaining low wear and stable friction across 25–800 °C;
- ✓ **enhanced lifespan:** post-aging of *Cu–15Ni–8Sn coatings* showed 3–4 times lower wear rates than as-sprayed versions, due to durable tribo-film formation; *NiMoAl + Ag + WS₂* delivered stable, low friction (down to 0.16 at 800 °C), and high wear resistance across all test temperatures, extending service life in extreme conditions;
- ✓ **compatibility with existing alloys:** *NiCrAlY + Al₂O₃ on Ni-based alloys* showed excellent adhesion and wear resistance across 25–700 °C, compatible with high-temperature alloys; *ZrO₂ coatings on Ti–Mo–Si alloy* formed crack-free microstructures with strong bonding, indicating good compatibility with biomedical alloys; *YSZ + graphene on SS316L* reduced friction by ~51% and wear rate by ~45%, proving suitability for stainless-steel substrates.

The use of Atmospheric Plasma Spray (APS) coatings represents a technologically advanced approach for enhancing the performance and durability of harrow discs employed in agricultural soil processing, particularly in abrasive, acidic, or stony soil conditions.

Compared to conventional surface protection methods such as hardfacing, flame spraying, or thermal diffusion treatments (e.g., boriding), APS coatings offer the following critical advantages:

- ✓ **Enhanced durability:** Ceramic and cermet coatings applied via APS (e.g., WC–CoCr or Cr₃C₂–NiCr) can increase the operational lifespan of harrow discs by a factor of 6 to 10, owing to their superior wear and corrosion resistance.
- ✓ **Excellent thermal stability:** APS coatings maintain structural and functional integrity under conditions of fluctuating temperatures and high friction, making them suitable for extreme agricultural environments.

- ✓ *Material versatility:* The APS process allows the application of a wide range of advanced materials, including smart ceramics, self-healing oxides, functionally graded materials (FGMs), and MAX phase compounds. This opens up significant potential for high-performance, next-generation agricultural tools.
- ✓ *Cost-effectiveness over time:* While the initial investment in APS technology is higher than traditional coating techniques, the cost-to-performance ratio becomes advantageous due to the extended service intervals and reduced maintenance or replacement frequency.

In summary, APS coating technology provides a sustainable and technically robust solution for increasing the reliability and efficiency of harrow discs. It aligns well with the demands of modern precision agriculture, where tool longevity and soil interaction performance are critical to operational success.

Additionally, future research should focus on developing smart materials capable of adapting to varying soil conditions, exemplified by: *Self-Healing Oxide Coatings* (NiCr–Al₂O₃ + Rare Earths, forms protective oxides that re-form after cracking), *Ti₂AlC MAX Phases with TiO₂ Skin Layer* (naturally forms TiO₂ upon wear, providing low friction and passivation); *Ceramic–Metal Gradient Coatings* (functionally graded materials–FGM, various compositions from ductile metal base to hard ceramic top layer), and *Ni–Re–Al–Y Oxide Dispersion Alloys* (smart alloy with oxide reinforcements, with high creep resistance, thermal oxidation stability, and regenerative oxide layer).

Another critical challenge is scaling up the production of high-durability materials while maintaining cost efficiency. Research should prioritize the discovery of affordable alternative materials and sustainable manufacturing techniques to ensure that wear-resistant disc harrows become more accessible to a broader market.

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Appendix A

Ref. No.	Techniques and Parameters Used for Tribological Characterisation of the APS Coatings
[66]	Microhardness (Vickers, 3N); ball-on-disc tribometer (CSM, Tribo-S-D-0000, 400 m distance, 6 N load, a contact pressure of 722.8 MPa, 20 cm/s sliding speed) against 6 µm Si ₃ N ₄ balls; porosity (pycnometer); SEM; TEM; XRD; DSC.
[67]	Ball-on-disc UMT-3 tribometer (10 N load, 0.105 m/s sliding speed at 25, 400, 800 °C for 60 min) against Φ10 mm Al ₂ O ₃ balls; microhardness (50 g load, 5 s); adhesive strength (WDW-200, ASTM C633, 0.5 mm/min speed); SEM; XRD; EDS.

Ref. No.	Techniques and Parameters Used for Tribological Characterisation of the APS Coatings
[68]	Ball-on-disc tribometer (MMQ-02 G, lubrication with SF 15 W-40 engine oil, 80 N and 100 N load, 400 r/min rotation speed, 30 min) against 6 μm Si_3N_4 balls; microhardness (100 g load for 10 s); elastic modulus (Nano-test 600); SEM; EDS.
[69]	Ball-on-disc tribometer (UMT-2 at 25 $^{\circ}\text{C}$, 40 N, 40 mm/s, 360 min; CSM-HT 1000 at 25, 200, 400, 600 $^{\circ}\text{C}$, 10 N, 400 rad/s, 30 min) against Si_3N_4 balls; microhardness (10 N, 15 s); XRD; SEM; EDS; TEM.
[70]	Ball-on-disk dry sliding wear (Anton Paar TRB ³ , 10 N load, 4 mm stroke length amplitude, 2 cm/s linear sliding speed, 15 min); nano-indentation (TriboIndenter TI 950, 5 mN load, 10 s); nanoscratch (TI 950, 2 mN and 5 mN load, 10 μ); SEM; XRD; TEM; DSC.
[71]	Reciprocating ball-on-disc tribometer (CFT-I, 9 Hz frequency, 5 mm amplitude, 3.24×10^4 reciprocations, 2 N, 5 N, 8 N load) against 5 mm ZrO_2 balls; hardness, elastic modulus, and elastic recovery (diamond-tipped nano-indentation tester NHT3, A. Paar); SEM; EDS; XPS, XRD; TEM.
[72]	Ball-on-disc tribometer (Ducom, at 150 rpm, 3600 s, 1 N load) against 6 mm stainless-steel ball; hardness and elastic modulus (micro-indenter MTR-3, Vickers tip, 1 N, 10 s); XRD; SEM; EDS.
[73]	Ball-on-disk dry sliding wear (Anton Paar TriTec, 5 N load, 2000 m sliding distance, 0.10 m/s speed, at 25, 400, 700 $^{\circ}\text{C}$) against 6 mm Al_2O_3 ball; SEM; XRD; micro-Raman spectroscopy (He:Ne laser).
[74]	Ball-on-disk tribometer (HSR-2M, 10 N load, 200 rpm speed, 9 Hz sliding frequency, 2.5 mm amplitude, 32,400 sliding cycles, 7 N) against 5 mm Al_2O_3 ball; SEM; XRD; ATR-FTIR; AFM; EPMA.
[75]	Ball-on-disk tribometer (UMT-3, 10 N load, 200 rpm rotational speed, 60 min at 25, 200, 400, 600, 800 $^{\circ}\text{C}$) against 10 mm Al_2O_3 ball; hardness (MH-5-VM, Vickers, 25 g load, 10 s); adhesive strength (CMT5205, ASTM C633) SEM; EDS; XRD; TEM; XPS.
[76]	Dry abrasive tests (TABER 5700 linear-type abrasimeter, 3000 cycles of 50.8 mm each, 10.8 N load); Wear Slurry Abrasion Response tests (SAR, ASTM G75) in Al_2O_3 suspension at 22.2 N for 2 h; SEM; EDS; XRD.
[77]	Ball-on-disk tribometer (UMT-2, 5 N load, 4 Hz frequency, 6 mm stroke length, 100 m sliding distance) against 4 mm WC-12Co ball; microhardness (microhardness tester 1000 type, 100 g load, 10 s); SEM; EDS; XRD.
[78]	Ball-on-disk tribometer (UMT-2, 20 N load, 4 Hz frequency, 5 mm stroke, 150 m sliding distance) against 4 mm Si_3Ni_4 , ZrO_2 , and GCr15 balls; electrochemical corrosion tests in 3.5% NaCl sol. (CHI 660 E); SEM; EDS; XRD.
[79]	SRV4 tribometer in linear dry sliding (5 N load, 5 Hz, 1 mm stroke, 900 s/4 h, at 25, 100, 200 $^{\circ}\text{C}$) against 10 mm 100Cr6 balls; LSM; SEM-FIB; EDS; XRD; Raman spectroscopy; scratch (Rockwell-C, 1–30 N load, 10 mm length).
[80]	MT-3 ball-on-disk tribometer (10 N load, 0.105 m/s speed, 60 min, at 25, 400, 800 $^{\circ}\text{C}$) against 10 mm Al_2O_3 balls; microhardness (microhardness tester MH-5-VM type, 500 g load, 10 s); SEM; EDS; XRD; TEM.
[81]	UMT pin-on-disk tribometer (50 N load, 5 m/s velocity, 900 s) against 35 μm WC stylus; microhardness (HXD-100 TMC, 300 g load, 15 s); adhesive strength (ASTM C633); SEM; EDS; XRD; TEM.
[82]	TR-20LE-CHM800 ball-on-disk tribometer (10 N load, 200 rpm, 60 min) against 10 mm WC ball; adhesion strength (Deflesko Positest-AT); micro-indenter (Micro test MTR3 type, 1 N load, 15 s); FESEM; EDS; XRD; TEM.

Ref. No.	Techniques and Parameters Used for Tribological Characterisation of the APS Coatings
[83]	Abradable rig test; erosion air-jet tester SJS type (ASTM G76 at 0.1 MPa, GE E50TF121 at 0.175 MPa); thermal diffusivity (Netzsch LFA 467 HT HyperFlash from room temperature up to 1200 °C at 200 °C intervals); SEM.
[84]	Wear and friction in dry sliding contact (Ducom TR-20, ASTM G90 standard, pin-on-disc method, 2000 rpm, 5 min); microhardness Shimadzu type (ASTM E-384); SEM; EDS; XRD.
[85]	Sliding, reciprocating, and vibrating test machine (SRV, 20, 46, 60, and 80 N loads, 1 mm stroke, 25 Hz, 20 min test duration) against a 10 mm steel ball; SEM; EDS.
[86]	Ball-on-disk tribometer (T-01, dry sliding, 5 N load, 500 m, 0.1 m/s sliding speed, 10,000 cycles) against 6 mm 100Cr6 steel ball; hardness (HV-1000, 1.96 N load); coating adhesion by pull-off test (Elcometer 510, 10 mm counterpart); SEM; XRD.
[87]	Dry sliding wear on tribological pairs (Amsler A 135-type machine, rolling disc from AISI 52100, 20 N load, 100 rpm, 60 min); microhardness (CETR UMT-2 micro-tribometer, Rockwell tip, 0–5 N progressive indentation force); SEM; EDS; XRD.
[88]	Ball-on-disk tribometer (UMT-2 CETR, dry sliding, 0.8 N load, 10 Hz, 0.05 m/s sliding speed, 3000 s, 5 mm stroke length, 150 m sliding distance) against 10 mm Al ₂ O ₃ ball; surface roughness (Mitutoyo Surftest SJ-210 Series); SEM; XRD.
[89]	UMT-3 ball-on-disk tribometer (10 N load, 0.104 m/s speed, 30 min at 25, 200, 500, 800 °C) against 10 mm Al ₂ O ₃ ball; microhardness (MH-5-VM, 4.9 N load, 5 s); impact resistance (QCJ-120, 1 kg, 0.5 m height, 4.9 J); SEM; XRD.
[90]	TRB ³ ball-on-disk tribometer (5 N load, 0.2 m/s speed, 2500 m sliding distance) against 6 mm Al ₂ O ₃ ball; micro-indentation (Duramin-40, 300 gf load, 10 s); nano-indentation (Hysitron PI 950, 950 µN/s load, 5 s); SEM; EDS; XRD.
[91]	UMT-3 ball-on-disk tribometer (10 N load, 200 rpm, 60 min at 25, 400, 800 °C) against 10 mm Al ₂ O ₃ ball; microhardness (MH-5-VM, 50 g load, 5 s); adhesive strength (ASTMC633); SEM; XRD.
[92]	UMT-3 ball-on-disk tribometer (10 N load, 200 rpm, 60 min) against 10 mm Si ₃ Ni ₄ , ZrO ₂ , GCr15, and Al ₂ O ₃ balls; microhardness (MH-5-VM, 4.9 N load, 5 s); SEM; EDS; XRD; TEM.
[93]	MFT 5000 ball-on-disk tribometer (5 N load, 355 rpm, 30 min at 25, 200, 400, 600, 800 °C) against 6 mm Al ₂ O ₃ balls; microhardness (DVS-1AT8, 200 g load, 10 s); SEM; EDS; XRD; Raman spectroscopy.
[94]	TR-23LE-CHM800 ball-on-disk tribometer (5 N load, 60 min at 25, 300, 600 °C) against 10 mm Al ₂ O ₃ ball; micro-indentation (MTR 3); FE-SEM; EDS; XRD; Raman spectroscopy; HR-TEM; XPS.
[95]	HT-1000 ball-on-disk tribometer (10 N load, 480 rpm, 60 min at 200, 800 °C) against 5 mm Si ₃ Ni ₄ ball; adhesive strength (GB/T 8642–2002, on universal testing machine (ETM205D)); SEM; EDS; XRD; Raman spectroscopy.
[96]	Sliding wear on tribological pairs (Amsler A 135 machine, AISI 52100 rolling disc, 20 N load/dry, 40 N/lubricated, 100 rpm, 600 s); microhardness (CETR UMT-2, Rockwell tip, 0–5 N indentation force); SEM; EDS; XRD.
[97]	In-operation testing on a gasoline fuel IC motor for 36 h; corrosion resistance (Potentiostat/Galvanostat (PARSTAT 4000type, ASTM G5–94)); SEM; EDS; XRD.
[98]	Sliding wear on tribological pairs (Amsler A 135 machine, AISI 52100 rolling disc, 20 N dry, 100 rpm, 3600 s); SEM; EDS.

Ref. No.	Techniques and Parameters Used for Tribological Characterisation of the APS Coatings
[99]	Pin-on-disk tribometer (dry, 10–30 N load, 0.5–1.5 m/s sliding velocity, 30 min) against cast-iron pin; microhardness (Vickers, 300 gf, 10 s); SEM; EDS; XRD.
[100]	MDW-02G ball-on-disk tribometer (15 N load, 2 Hz, 20 mm stroke length, 30 min, dry) against 6.35 mm Si ₃ Ni ₄ ball; adhesive strength (GB/T 8642–2002); microhardness (Vickers, 9.8 N load, 10 s); SEM; EDS; XRD.
[101]	NTR2+ ball-on-disk nanotribometer (1 N load, 90 rpm, 2000 m sliding distance, distilled water) against 0.5 mm WC ball; cavitation erosion (ASTM G32, 20 kHz, 50 µm amplitude) SEM; EDS.
[102]	Plint TE 77 high-frequency reciprocating rig for wear and friction tests; scuffing test (2 h, 8 mL engine oil); endurance test (64 h); engine dyno test (500 h polycyclic endurance test); SEM; EDS, FIB, XRD.

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