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EVOLUTION OF THE COLD SPRAY TECHNOLOGY FOR SURFACE ENGINEERING AND ADDITIVE MANUFACTURING: A BIBLIOMETRIC ANALYSIS

The aim of this study is to conduct a comprehensive bibliometric analysis of the global scientific literature on the cold spray (CS) process in order to identify its major evolutionary trends, provide insights into the research trends in the field, and highlight the current state and future prospects of the technology for wear-resistant coating applications. The study is based on the analysis of a dataset comprising 4630 scientific publications indexed in the Science Citation Index Expanded database of the Web of Science from 1996 to 2026. VOSviewer 1.6.20 software was employed to visualize international collaboration networks, keyword co-occurrence, and thematic clusters. The results reveal an exponential increase in scientific interest in the CS process beginning in the early 2000s. China (28.7%), the United States (18.4%), and Canada (10.4%) are the leading countries in terms of publication output. The keyword co-occurrence analysis identified four major thematic clusters representing the evolution of research in the field. It was demonstrated that the current focus of scientific research has shifted from the fundamental physics of gas-dynamic particle deposition to applied materials science, where the dominant trend is the development of metal-matrix composite coatings to enhance the tribological performance of engineering components. The scientific novelty of this study lies in the first comprehensive bibliometric assessment of the global development of CS technology from the perspectives of tribology and surface engineering. The findings demonstrate an evolutionary transition in research interests from optimizing the adhesion of individual particles to developing multifunctional wear-resistant coatings and additive restoration of worn surfaces. The results provide a roadmap for researchers and engineers in surface engineering by identifying the most promising directions for future research, particularly the incorporation of hard reinforcing phases (carbides and oxides) into ductile matrices to produce composite coatings with superior wear resistance.

Keywords: *thermal spraying; cold spray; tribology; additive manufacturing; protective coatings; wear-resistant coatings; composite coatings; surface treatment; surface layer.*

Introduction. Modern mechanical engineering and the aerospace industry require innovative technological solutions for producing high-performance coatings. Among the available technologies for the protection and repair of components, the cold spray (CS) process is considered one of the most promising methods [1]. Traditional thermal spray methods often cannot achieve the required coating quality due to high operating temperatures [2], which can lead to carbide decarburization [3], oxidation, thermal stresses in the material, and other undesirable effects [4, 5]. Coating formation during the CS process results from the kinetic energy of powder particles accelerated to supersonic velocities [6]. Compressed gas (nitrogen, helium, or air) passing through a De Laval nozzle accelerates the particles [7]. When the powder particles impact the substrate, adiabatic shear instability occurs [8]. The particles undergo intense plastic deformation, resulting in strong mechanical and metallurgical bonding with the substrate surface [9].

The key difference between CS and other coating methods is that the process is carried out at temperatures well below the particles' melting point. This enables preservation of the powder's original properties, as the particles remain in the solid-state during deposition [10]. Therefore, the method has great potential for practical applications, especially for depositing coatings on materials sensitive to high temperatures (aluminum, magnesium, and titanium alloys, composites, plastics, etc.), as well as when using fine and composite powders.

The deposition of composite powders, which combine a ductile metal matrix with hard particles (carbides, oxides, etc.), enables the production of wear-resistant coatings [11, 12]. In addition to improving the tribological properties of the coatings, the addition of hard particles to the powder mixture plays a key role in surface activation prior to deposition by removing the oxide film and creating the necessary surface roughness, thereby promoting the formation of strong adhesive bonds. During coating formation, the hard particles become embedded in the metal matrix, further compacting the previously deposited layers and producing a work-hardening effect [13]. This enables the production of multifunctional coatings with a unique combination of ductility and wear resistance, with properties largely determined by the composition and structure of the initial powder mixture [14].

The absence of structural and phase changes in both the substrate and coating materials opens new opportunities for the application of CS in additive manufacturing [15, 16], enabling the transition from simple repair to the full-scale fabrication of metal components [17]. The technology enables the manufacturing of parts with complex geometry [18], close to the final shape, with virtually no size limitations [19], and with a lower environmental impact than many other industrial technologies [20].

Problem statement. This study is not focused on describing the features of the CS process or the phenomena occurring during deposition. Instead, it aims to investigate how research in this field has evolved over time, who the leading contributors to the method's development are, which topics have gained popularity, and what the prospects for future research are.

The aim of this study is to conduct a comprehensive bibliometric analysis of the global scientific literature on the CS process to identify the main evolutionary trends, provide an overview of research dynamics in this field, and highlight the current state and future prospects of the method for producing wear-resistant coatings.

Research objectives are:

- to investigate changes in the number of publications related to the CS process;
- to identify the leading countries and the most active authors conducting research in this field, and to determine the collaboration links between them in order to understand global research cooperation;
- to identify the most highly cited journals publishing research results on the CS;
- to determine the place of wear-resistant coating deposition within the overall research structure;
- to identify new directions in the development of the method and prospects for future research.

Methodology. A bibliometric analysis was applied in this study. It is based on the use of mathematical and statistical methods for analyzing publication datasets. This approach enables assessment of the accumulated body of knowledge and identification

of the key stages of evolution and development trends in a specific research field [21, 22].

To provide a reliable basis for the analysis, including the most highly cited publications on CS, the Science Citation Index Expanded (SCIE) database of the Web of Science platform was selected. This database contains the most significant publications across all research fields [23].

To include the maximum number of relevant publications, only general search terms were used in the search query: ("cold spray*" OR "gas dynamic spray*" OR "kinetic deposition*"), making it possible to identify the development trends of the method.

The literature search was performed on May 14, 2026. To ensure a high-quality dataset, restrictions were applied only to the document type. Excluding all secondary publication types enabled a focus on the primary scientific information in research articles, conference proceedings, review articles, and book chapters.

The retrieved publication dataset was processed using the specialized software VOSviewer 1.6.20 [24]. This tool enables the construction and visualization of complex relationship networks. Within this study, the following were analyzed:

- international collaboration networks (to visualize partnerships between countries);
- keyword co-occurrence networks (to identify the main research clusters);
- the network of the most highly cited publications.

The global publication trends were visualized using the online platform Ultimaps [25]. This made it possible to obtain a detailed map of scientific productivity by country and region.

Results. The bibliometric search in the SCIE database identified 4630 scientific publications related to the CS process. Their distribution by document type is presented in Table 1.

Table 1

Document types of CS research

Document type	Number of publications	% of 4630
Article	3939	85.076
Proceeding Paper	759	16.393
Review Article	211	4.557
Book Chapters	41	0.886

The analysis of publications by year revealed a rapid increase in the number of studies beginning in the early 2000s (Fig. 1).

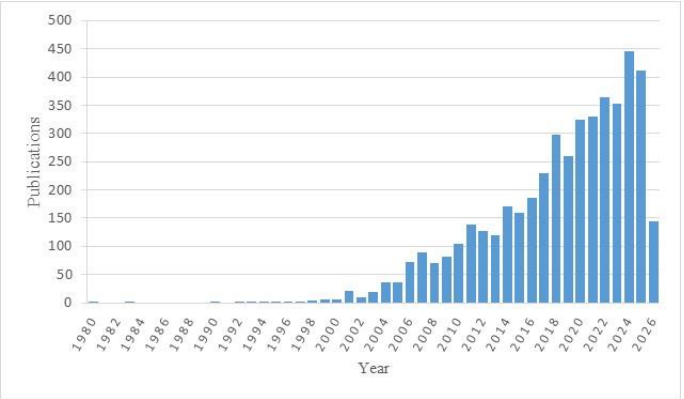


Fig. 1. Publications on CS by year

Research on the CS process covers a wide range of scientific fields, among which Materials Science accounts for the largest share (74.2%) of all publications, followed by Physics (24.9%), Engineering (18.7%), Metallurgy (17.46%), and Chemistry (9.72%) (Table 2).

Table 2

Key research areas of publications on CS

Research area	Number of publications	% of 4630
Materials science	3435	74.190
Physics	1151	24.860
Engineering	866	18.704
Metallurgy Metallurgical engineering	808	17.451
Chemistry	450	9.719
Science technology Other topics	183	3.952
Mechanics	137	2.959
Thermodynamics	73	1.577
Nuclear science technology	69	1.490
Automation control systems	54	1.166

The main journals publishing research on the CS process were also identified: Journal of Thermal Spray Technology (16.02% of all publications), Surface and Coatings Technology (11.58%), and Coatings (3.05%) (Table 3).

Table 3

Key journals publishing articles on CS

Journal	Number of publications	% of 4630
Journal of Thermal Spray Technology	742	16.026
Surface and Coatings Technology	536	11.577
Coatings	141	3.045
Applied Surface Science	90	1.944
Surface Engineering	86	1.857
Journal of Alloys and Compounds	71	1.533
Materials	64	1.382
Materials Science and Engineering: A Structural Materials: Properties, Microstructure and Processing	64	1.382
Materials & Design	54	1.166
Additive Manufacturing	51	1.102

The leading publishers were Elsevier (1785 publications), Springer Nature (1072), and MDPI (304) (Table 4).

The analysis of geographical productivity identified three leading countries that account for more than half of all publications on the CS process worldwide: China – 1329 publications (28.7%), the United States – 854 publications (18.4%), and Canada – 480 publications (10.4%) (Table 5).

Table 4

Leading publishers of CS publications

Publisher	Number of publications
Elsevier	1785
Springer Nature	1072
MDPI	304
Taylor & Francis	161
Wiley	112
Trans Tech Publications Ltd	83
Asm International	81
IOP Publishing Ltd	63
Amer Chemical Soc	60
Amer Soc Mechanical Engineers	55

Table 5

Countries and regions with the largest number of publications on CS

Country/Region	Number of publications	% of 4630
People's Republic of China	1329	28.704
USA	854	18.445
Canada	480	10.367
France	383	8.272
India	297	6.415
Germany	267	5.767
Japan	260	5.616
Russia	238	5.140
South Korea	224	4.838
Italy	202	4.363
Australia	191	4.125
England	148	3.197
Spain	118	2.549
Ireland	111	2.397
…	…	…
Switzerland	30	0.648
Ukraine	28	0.605
Sweden	25	0.540
Belgium	19	0.410

The online platform Ultimaps was used to create a detailed map, enabling accurate visualization of the most productive countries (Fig. 2).

International collaboration is a characteristic feature of scientific research, as demonstrated by the collaboration network of countries publishing research on the CS process (Fig. 3). The network includes countries with more than five publications. The nodes represent countries and their contribution (number of publications), while the connecting lines indicate the strength of collaboration (number of co-authored publications). The resulting network shows that China is the most central and highly connected node, highlighting its major role in global scientific collaboration. The United States, France, Germany, and Canada also actively participate in international research collaborations.

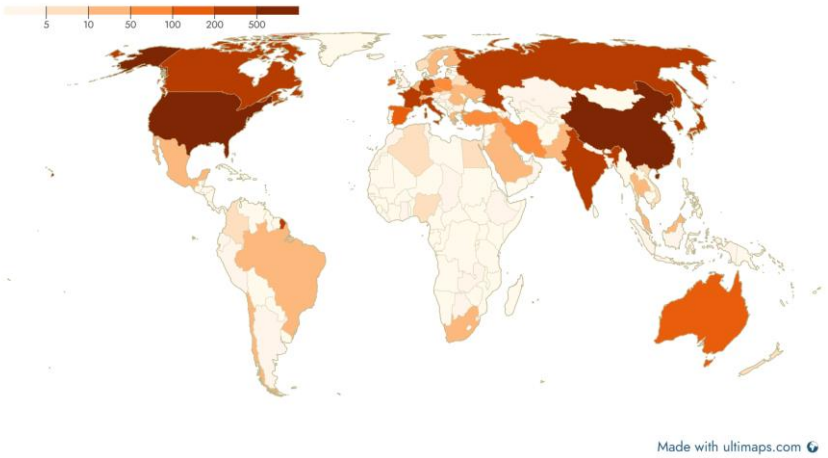


Fig. 2. Global distribution of publications on CS.

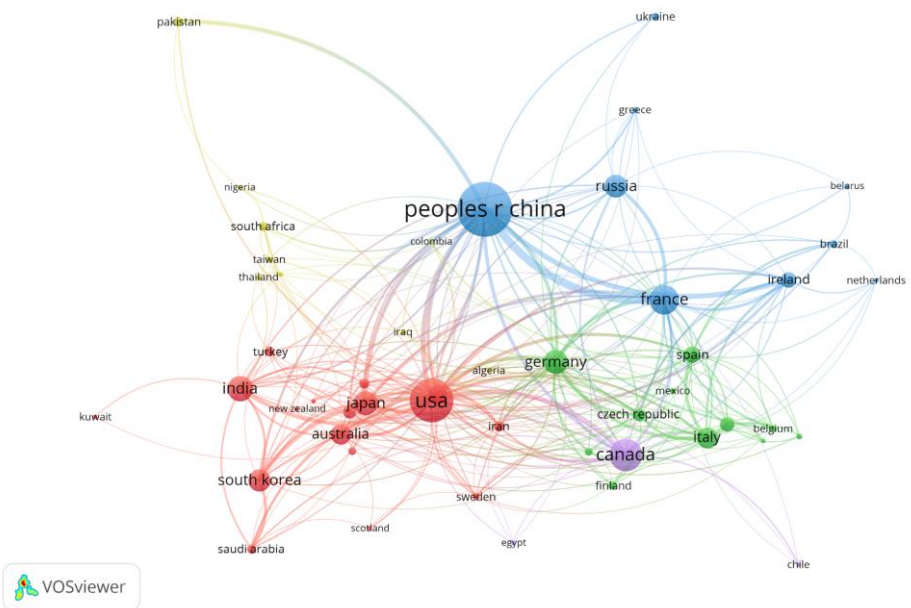


Fig. 3. International collaboration between countries in CS research. Interactive visualization: https://tinyurl.com/2yykdtqp (accessed: 10.07.2025).

It can also be observed that countries such as Egypt, Sweden, and Taiwan, together with Thailand and Vietnam, began active collaboration around 2021–2022 (Fig. 4). This indicates the continuing expansion of CS research in both developed and emerging scientific communities.

Citation analysis showed an average of 26.65 citations per document and identified the publications that serve as the main references for subsequent studies (Fig. 5). The citation network includes authors with at least 200 citations. As a result, the most highly cited publications were identified:

1. Assadi H., Gärtner F., Stoltenhoff T., Kreye H. Bonding mechanism in cold gas spraying. *Acta Materialia*. 2003. Vol. 51, Is. 15. P. 4379-4394. https://doi.org/10.1016/S1359-6454(03)00274-X. (1519 citations)

2. Schmidt T., Gärtner F., Assadi H., Kreye H. Development of a generalized parameter window for cold spray deposition. *Acta Materialia*. 2006. Vol. 54, Is. 3. P. 729-742. https://doi.org/10.1016/j.actamat.2005.10.005. (1007 citations)

3. Assadi H., Kreye H., Gärtner F., Klassen T. Cold spraying - A materials perspective. *Acta Materiala*. 2016. Vol. 116. P. 382-407. https://doi.org/10.1016/j.actamat.2016.06.034. (790 citations)

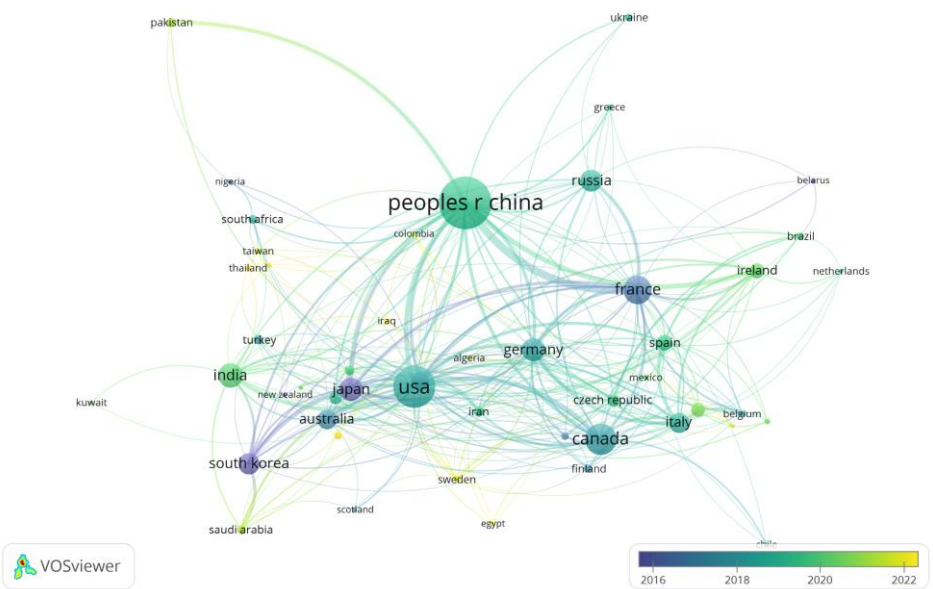


Fig. 4. International collaboration between countries, showing the average publication year for CS research. Interactive visualization: https://tinyurl.com/2yykdtqp (accessed: 10.07.2025).

It is immediately evident that the most highly cited recent publications are related to additive manufacturing, indicating that this has become one of the most important and promising directions in the development of the CS process:

1. Yin S., Cavaliere P., Aldwell B., Jenkins R., Liao H., Li W., Lupoi R. Cold spray additive manufacturing and repair: Fundamentals and applications. *Additive*

Manufacturing. 2018. Vol. 21. P. 628-650. https://doi.org/10.1016/j.addma.2018.04.017. (618 citations)

2. Maleki E., Bagherifard S., Bandini M., Guagliano M. Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities. *Additive Manufacturing*. 2021. Vol. 37. 101619. https://doi.org/10.1016/j.addma.2020.101619. (498 citations)

3. Kanishka K., Acherjee B. A systematic review of additive manufacturing-based remanufacturing techniques for component repair and restoration. *Journal of Manufacturing Processes*. 2023. Vol. 89. P. 220-283. https://doi.org/10.1016/j.jmapro.2023.01.034. (213 citations)

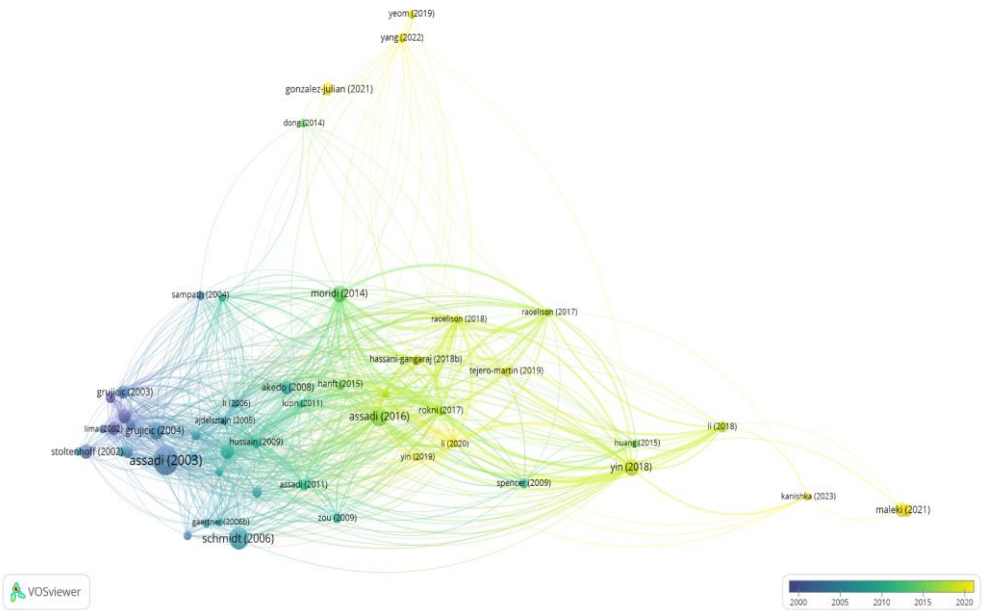


Fig. 5. Network of the most highly cited publications on CS. Interactive visualization: https://tinyurl.com/2bjozkj4 (accessed: 10.07.2025).

According to data from the SCIE database of the Web of Science, 7723 unique keywords were identified in publications on the CS process, of which 78 appeared 25 or more times (Fig. 6).

Each node represents a keyword, while the connecting lines indicate keyword co-occurrence. The size of each node is proportional to its level of connectivity with other keywords, and the thickness of the connecting lines reflects the frequency of their co-occurrence.

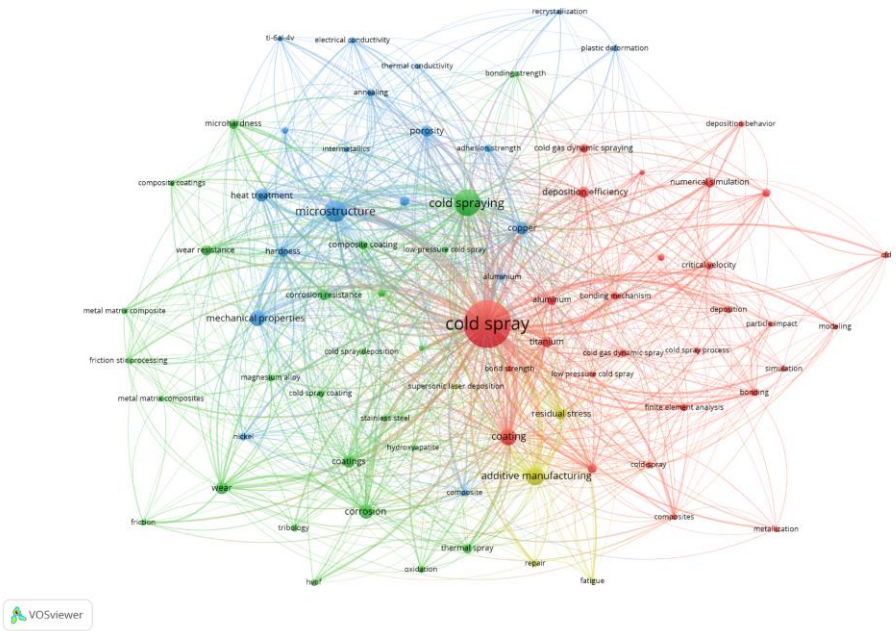


Fig. 6. Keyword co-occurrence network in publications on CS. Interactive visualization: https://tinyurl.com/27vurmn7 (accessed: 10.07.2025).

Table 6 presents the keywords most frequently occurring in publications.

Table 6

Most frequently occurring keywords in publications on CS

Keyword	Number of occurrences
cold spray	1790
cold spraying	568
microstructure	392
additive manufacturing	274
coating	223
mechanical properties	197
corrosion	164
heat treatment	134
copper	126
wear	124

To analyze the development of the CS process and identify current research trends, a keyword network based on publication year was generated (Fig. 7).

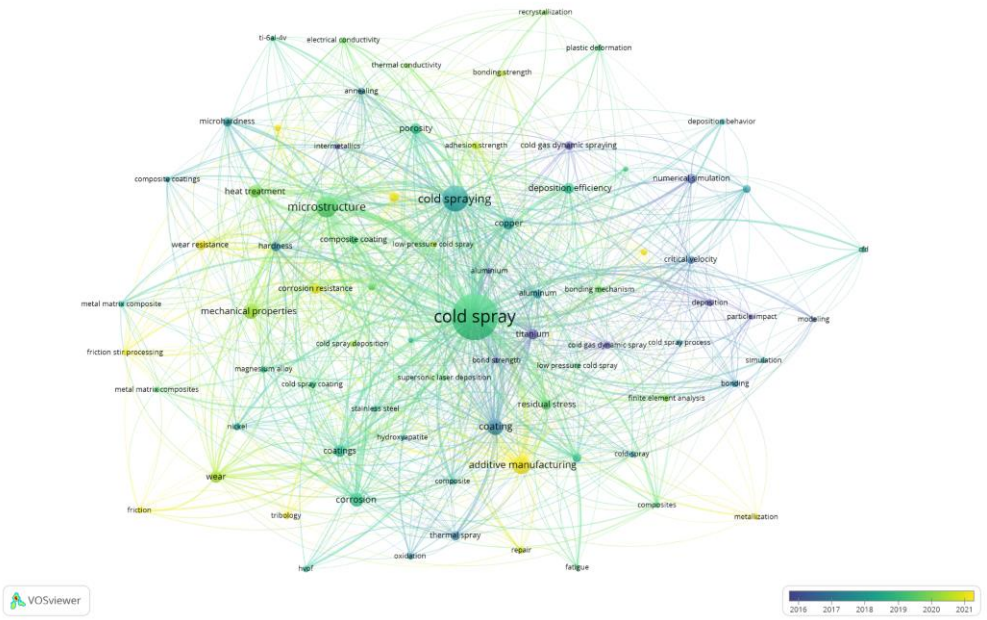


Fig. 7. Evolution of CS research. Interactive visualization: https://tinyurl.com/27vurmn7 (accessed: 10.07.2025).

The keyword analysis identified four main thematic clusters representing the structure of scientific research in the field of CS:

1. Red cluster: Fundamental research and process physics. Publications in this cluster mainly belong to the early stages of the method's development and focus on understanding the basic mechanisms of coating formation and their theoretical background, including two-phase gas dynamics, high-velocity particle impact, and the formation of adhesive bonds. Computational fluid dynamics and finite element analysis were widely used to determine particle temperature, deformation, and the critical deposition velocity (primarily for pure metals such as aluminum, copper, and titanium) required for particle bonding with the substrate. The most frequently used keywords include cold spray, numerical simulation, finite element analysis, particle velocity, bonding, and particle impact.

2. Blue cluster: Coating structure. This cluster represents the transition from theoretical modeling to coating deposition and evaluation of coating quality. The main research focus is on coating microstructure and porosity. During this stage, numerous studies investigated post-deposition heat treatment, its influence on the coating microstructure, recrystallization processes, and improvements in mechanical properties. The main keywords include microstructure, porosity, heat treatment, annealing, and mechanical properties.

3. Green cluster: Composite coatings and tribology. Research in this cluster focuses on the performance characteristics of coatings. The need to improve the physical and mechanical properties of coatings and increase process efficiency led to the application of composite powders (metal matrix composites). Considerable attention has been devoted to the development of wear-resistant coatings. The most frequently

used keywords include wear resistance, composite coatings, metal matrix composites, corrosion resistance, friction, and wear.

4. Yellow cluster: Additive manufacturing and repair. This is the most recent research direction and reflects the transition from coating deposition to three-dimensional printing (additive manufacturing) and the repair of large metal components. Studies on the fatigue behavior of coated parts and additively manufactured specimens demonstrate the growing interest in applying the CS process to critical components subjected to cyclic loading. The most frequently used keywords include additive manufacturing, repair, and fatigue.

In summary, the analysis of the networks presented in Figs. 6 and 7 reveals a clear evolution of scientific research. Researchers have gradually shifted from developing the theoretical foundations of the process, focusing on modeling physical phenomena, particle bonding, and microstructural analysis, toward application-oriented research aimed at solving practical engineering problems, such as improving wear resistance and corrosion resistance. Particularly notable is the rapid development of additive manufacturing and component repair, which is opening new opportunities for innovative applications in high-technology industries.

Conclusions. Based on the bibliometric analysis of 4630 scientific publications from the SCIE database of the Web of Science related to the CS process, the following conclusions can be drawn:

1) The CS process demonstrates a rapid exponential growth in scientific interest, which began in the early 2000s and continues to accelerate. The largest share of research is produced by authors affiliated with China, the United States, and Canada, which together account for more than 57% of all publications in this field.

2) The majority of publications are concentrated in the fields of Materials Science (74.2%) and Engineering (18.7%). The leading journals publishing research results are specialized surface engineering journals, particularly Journal of Thermal Spray Technology (16.02%) and Surface and Coatings Technology (11.58%).

3) The keyword network analysis identified four major thematic clusters that clearly illustrate the evolution of the CS process: fundamental research and process physics, coating structure, composite coatings and tribology, and additive manufacturing and repair.

4) The most important application-oriented research direction is the development of wear-resistant and corrosion-resistant metal matrix composite coatings. The analyzed studies confirm that the addition of hard particles (carbides and oxides) to powder mixtures is highly effective not only for surface activation and layer densification but also for improving the tribological properties of coatings.

5) A clear transition of the CS process from conventional coating deposition toward additive manufacturing and repair applications can be observed. The ability of the technology to produce thick deposits without structural or phase changes in either the coating or the substrate materials, together with the absence of significant residual thermal stresses, provides unique opportunities to restore worn components to their original geometry. This is of critical importance for modern mechanical engineering and for improving the operational reliability of engineering components.

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ЕВОЛЮЦІЯ МЕТОДУ ХОЛОДНОГО ГАЗОДИНАМІЧНОГО НАПИЛЮВАННЯ ДЛЯ ІНЖЕНЕРІЇ ПОВЕРХНІ ТА АДИТИВНОГО ВИРОБНИЦТВА: БІБЛІОМЕТРИЧНИЙ АНАЛІЗ

Метою роботи є комплексний бібліометричний аналіз світової наукової літератури, присвяченої методу холодного газодинамічного напилювання (ХГН) для виявлення ключових еволюційних тенденцій, отримання уявлення про динаміку досліджень у напрямі ХГН, висвітлення сучасного стану і перспектив розвитку методу для отримання зносостійких покриттів. Дослідження базується на аналізі масиву з 4630 наукових публікацій, проіндексованих у базі даних Science Citation Index Expanded мережі Web of Science у період з 1996 по 2026 рік. Для візуалізації мереж міжнародної співпраці, спільного використання ключових слів і побудови тематичних кластерів застосовано програмне забезпечення VOSviewer 1.6.20. Встановлено експоненційне зростання наукового інтересу до методу ХГН, починаючи з початку 2000-х років. Лідерами за кількістю публікацій є Китай (28,7 %), США (18,4 %) та Канада (10,4 %). Аналіз ключових слів дозволив виділити чотири основні тематичні кластери, що відображають еволюцію досліджень. Доведено, що сучасний фокус наукової уваги змістився від фундаментальної фізики газодинамічних процесів до прикладного матеріалознавства, де домінуючим трендом є розробка металоматричних композиційних покриттів для підвищення триботехнічних характеристик деталей. Наукова новизна отриманих результатів полягає у тому, що вперше на основі комплексного бібліометричного аналізу систематизовано світовий досвід розвитку методу ХГН крізь призму трибології та інженерії поверхні. Доведено еволюційний перехід дослідницьких інтересів від оптимізації адгезії одиничних частинок до створення багатофункціональних зносостійких шарів та адитивного відновлення зношених поверхонь. Отримані результати формують дорожню карту для фахівців у галузі інженерії поверхні, вказуючи на найбільш перспективні вектори подальших досліджень: застосування твердих армуючих фаз (карбідів, оксидів) у пластичних матрицях для формування композиційних покриттів із високою стійкістю до зношування.

Ключові слова: *газотермічне напилювання, холодне газодинамічне напилювання, трибологія, адитивне виробництво, захисні покриття, зносостійкі покриття, композиційні покриття, поверхнева обробка, поверхневий шар.*

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