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Review

Bibliometric Analysis and Visualization of Nanoindentation Research

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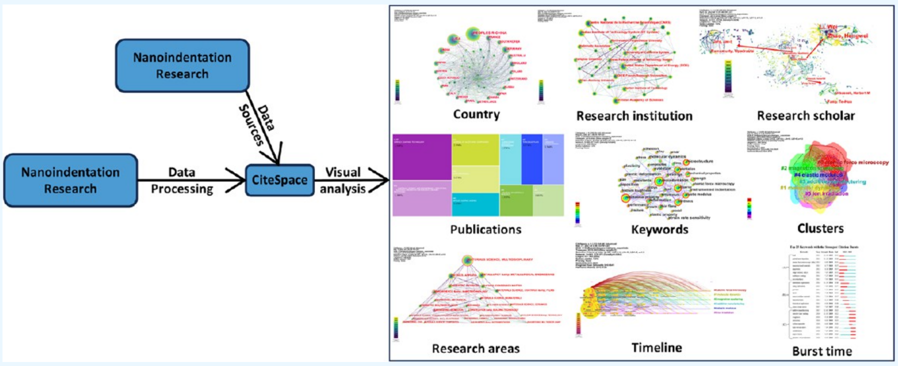

ABSTRACT: Nanoindentation has gained significant attention as a method for the quantitative characterization of mechanical properties of materials at micro- and nanoscales. This study investigates trends in nanoindentation technology by visualizing and analyzing relevant publications. To achieve this, CiteSpace was utilized to analyze 14 373 papers from the Web of Science core database published between 2013 and 2022. The analysis examined the status and trends in nanoindentation technology, focusing on the publication counts, contributing countries, institutions, authors, and keywords. The results indicate a growing number of publications related to nanoindentation technology globally, with China leading in publication output. Upadrasta Ramamurty is recognized as the most prolific author, while the work of W.C. Oliver and G.M. Pharr has received substantial citations. Six research hotspots and their associated content are identified as current frontiers in this field. Future investigations may concentrate on the applicability range, measurement accuracy, and theoretical modeling of this technique. This review aims to assist scholars interested in nanoindentation technology in quickly identifying research priorities from a new perspective and anticipating the future trajectory of this field.

1. INTRODUCTION

In recent years, the rapid development of nanostructures and materials has redirected research focus from the microscale to the nanoscale. This transition has resulted in a growing demand for advanced materials characterization techniques, which are continuously challenged at the nanoscale.[1] Consequently, significant advancements have been made in various techniques, including scanning electron microscopy (SEM),[2−6] transmission electron microscopy (TEM),[7−12] and X-ray tomography.[13−18] Notably, nanoindentation has garnered considerable attention from researchers due to its ability to measure the mechanical properties of materials at the nanoscale. Materials scientists are focused on integrating the macroscopic mechanical properties of materials with their intrinsic microstructural parameters to achieve desired properties through microstructural modulation.[19] Nanoindentation effectively bridges the gap between the macroscopic and microscopic aspects of materials. This technique employs computer-controlled loads to press a rigid indenter with a defined geometry into the surface of the material. Concurrently, a high-resolution displacement transducer records the indentation depth, facilitating the generation of a load−displacement curve. As a result, mechanical behaviors such as hardness and modulus of elasticity can be accurately measured at the micro/nanoscale.[20−31]

Nanoindentation has become a pivotal method for characterizing the mechanical properties of materials, with its application evolving over time. Figure 1 illustrates the timeline of the development of nanoindentation technology. Originally proposed by J.A. Brinell in 1900 to assess the mechanical properties of metal alloys, indentation methods have since been widely

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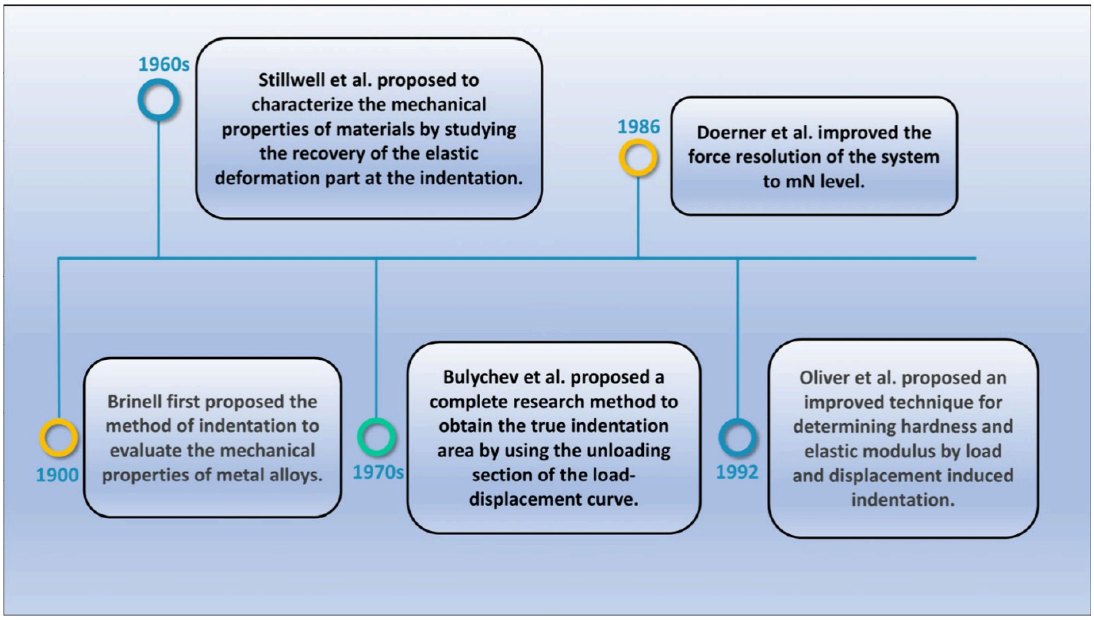

Figure 1. Timeline of the development of nanoindentation technology.

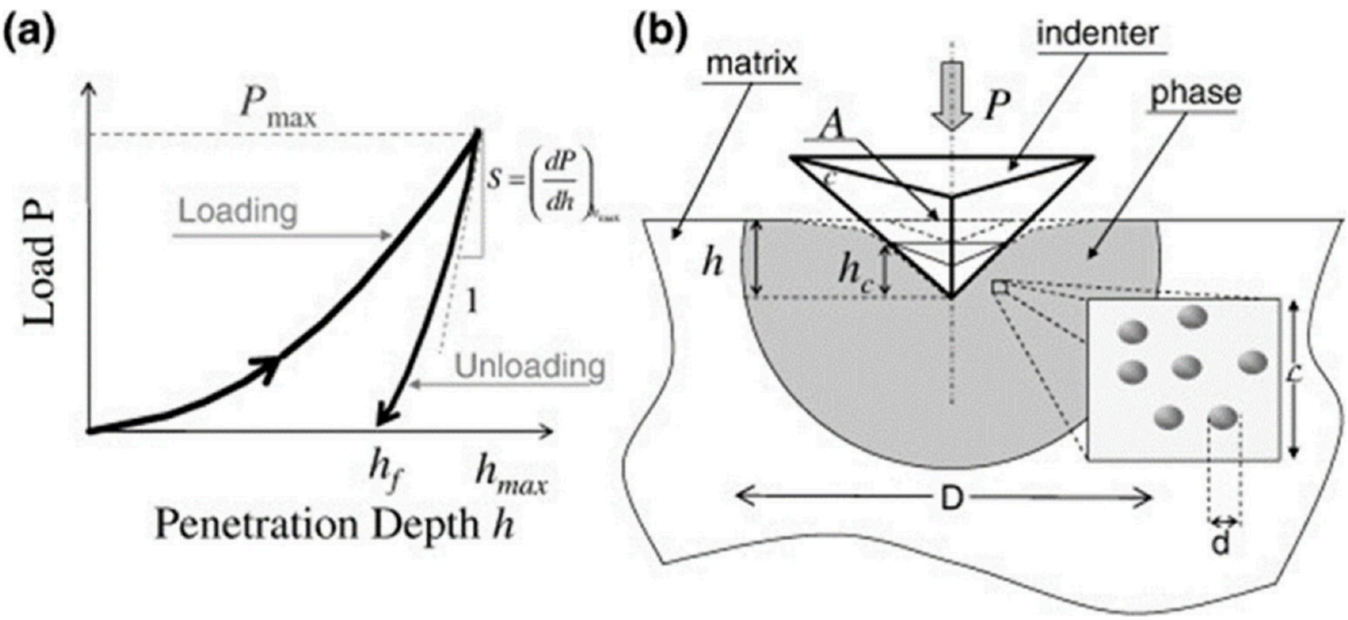

Figure 2. (a) Typical load-indentation depth (P−h) curve and (b) schematic representation of an indentation test using a Berkovic indenter on a homogeneous phase. Reproduced with permission from ref 38. Copyright 2008 Elsevier Ltd.

adopted and continuously refined. In the 1960s, Stillwell and Tabor[32] introduced a method that involved applying a load to a sharp prismatic indenter and pressing it into the test material. This process creates an indentation on the material's surface once a specific depth is reached. Upon unloading, the mechanical properties of the material are determined by examining the recovery of the elastically deformed region at the indentation. In the 1970s, Bulychev et al.[33] systematically analyzed load-depth curves obtained from experiments and proposed a method that utilizes the unloading segment of the load−displacement curve to determine the true indentation area. This marked the early development of modern indentation technology. Later, Pethica[34] utilized a specialized microhardness tester to create indentations at the nanoscale, thereby investigating the injection of ions into a metal matrix to enhance its surface properties. Despite this, the advancement of nanoscale indentation technology remains ongoing. In 1986, Doerner and Nix[35] enhanced the force resolution to the millinewton level, demonstrating the feasibility of applying indentation technology at the microscopic scale. By 1992, Oliver and Pharr[36] developed an improved technique for determining hardness and the modulus of elasticity based on load and displacement during indentation, further developing Sneddon's earlier work.[37] The Oliver-Pharr method refines the fitting of the initial segment of the unloading section by employing a power function instead of a polynomial function, thereby yielding more accurate results regarding the mechanical properties of the tested materials. Figure 2 illustrates the load-indentation depth curves obtained from these experiments, along with a schematic

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diagram of the indentation tests using a Berkovic indenter on the homogeneous phase.

CiteSpace, developed by Professor Chaomei Chen, is a freely available tool designed for interactive and exploratory analysis of scientific fields, encompassing both single specialties and multiple interconnected scientific frontiers.[39] The software facilitates the understanding of a subject by visualizing and analyzing relevant literature. Utilizing a path-finding network algorithm alongside cocitation analysis theory, this software examines the citation networks, author collaboration networks, and the evolution of research topics sourced from databases such as Web of Science, Scopus, and Dimensions. This approach aids in identifying trends and hotspots within the research field.[40] Several scholars have utilized CiteSpace in their respective fields of study. For instance, Liu et al.[41] employed it to visualize electrochemiluminescence sensing technology, emphasizing the necessity for further advancements across diverse applications. Similarly, Li et al.[42] utilized CiteSpace to examine the global progress of green buildings, discussing current advancements, challenges, and future prospects in this sector. Zhang et al.[43] systematically analyzed the literature on sustainable urbanization using CiteSpace, drawing from databases such as Web of Science, Scopus, and the China National Knowledge Infrastructure. Their study examined the current state of research, the historical development, and potential trends in this area. Likewise, Wang et al.[44] used CiteSpace to investigate the progress and status of urban metabolism from various perspectives, revealing key research areas and predicting future trends. Additionally, Zheng et al.[45] focused on the application of deep learning methods using CiteSpace for intelligent detection of pavement distress. Their bibliometric analysis provides insights into the field and highlights existing gaps, challenges, and future research directions aimed at advancing both research and practical applications. In another study, Chen et al.[46] employed CiteSpace to systematize the current state of research on wind-powered building skin from an interdisciplinary perspective, with the intention of attracting more attention to this innovative technology and encouraging further development in this field.

Thus, this study presents a visual and analytical overview of nanoindentation research articles from the Web of Science database using CiteSpace. The objective is to consolidate existing knowledge, review the current state of the research field, and contribute to the ongoing development of the technology.

2. METHODOLOGY AND DATA

2.1. Data Source. The data for this study were sourced from the Web of Science Core Collection, an independent global citation repository that encompasses leading journals worldwide.[47] Given that this database contains a significant number of publications on nanoindentation technology, it serves as an appropriate and reliable source for the present study.

For data retrieval, the Web of Science Core Collection database was selected, focusing on the theme of "nanoindentation" within the time span of 2013 to 2022 and restricting the document type to articles. The search results were merged using the logical operator "and" to filter for articles that met all specified criteria. Only peer-reviewed journal articles are considered in this study, as they generally reflect higher quality and more reliable advancements in nanoindentation technology. The literature data, including full records and cited references, were exported as a plain text file using the Web of Science system. A total of 14,373 documents were retrieved using these methods at the time of export. The export was conducted on 19 April 2023 to minimize the impact of potential data changes. Of the retrieved documents, 99.03% were written in English. Notably, the language of publication does not necessarily reflect the country of origin, as English is the predominant language in the scientific community.[48]

2.2. Analysis Method. In this study, the advanced version of CiteSpace (64-bit) was selected as the primary tool for a comprehensive analysis of the exported documents. The data processing time frame spans from 2013 to 2022, with each year treated as a separate time slice. This resulted in ten distinct time slices for analysis. The vocabulary sources chosen include the Topic, Abstract, Keywords (DE), and Keyword Plus (ID), while the node types selected are coauthors, institutions, countries, keywords, and disciplines. The g-index was set at "k = 25" for node screening, with a threshold defined as "TOP = 50".[49] Nodes such as keywords, coauthors, institutions, and countries were selected to construct a knowledge graph for further analysis.

3. RESULTS AND DISCUSSION

3.1. Nanoindentation Technology Research Dynamics. *3.1.1. Temporal Characteristics of the Volume of Publications.* The body of literature in a specific research field often reflects its development, serving as a key indicator of emerging trends. Between 2013 and 2022, 14,373 papers were published on nanoindentation, with an average of 1,437 publications per year. The temporal distribution of these publications is illustrated in Figure 3.

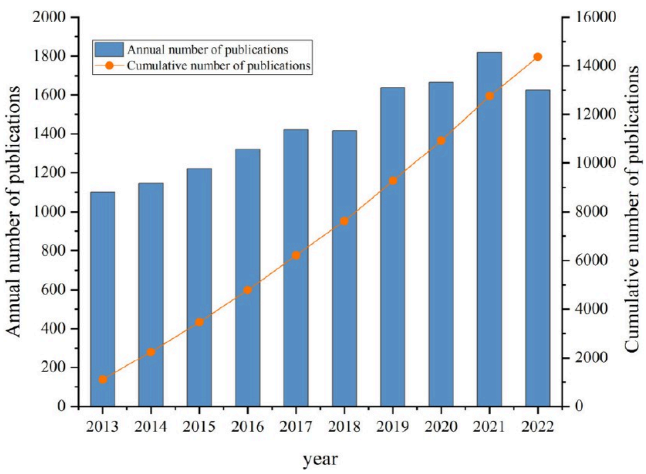

Figure 3. Volume of publications based on time series.

The time series analysis of publication numbers reveals a consistent upward trend in annual publications from 2013 to 2022, with the count exceeding 1,000 each year. The slight decline observed in 2022 may be attributed to the incomplete retrieval of certain articles from the Web of Science Core Collection during data collection. A correlation analysis between the year and the total number of articles reveals a strong linear relationship, described by the function $y = 1485.7x - 2990216$, with a coefficient of determination (R^2) of 0.9949. Furthermore, the analysis of both annual and cumulative publications suggests that nanoindentation technology has been evolving in recent years, with an increasing body of academic research dedicated to it. While the number of publications on nanoindentation has steadily grown since the early 21st century, particularly over the past decade, its total publication count remains lower than that of material characterization techniques, such as atomic force microscopy (AFM). For such techniques, broader scholarly engagement and utilization typically drive their rapid development.

3.1.2. Visualization and Analysis of Collaborative Networks of Countries and Research Institutes. This study employs CiteSpace to generate a collaborative network map of countries and research institutes engaged in nanoindentation technology. The visualization, presented in Figures 4 and 5,

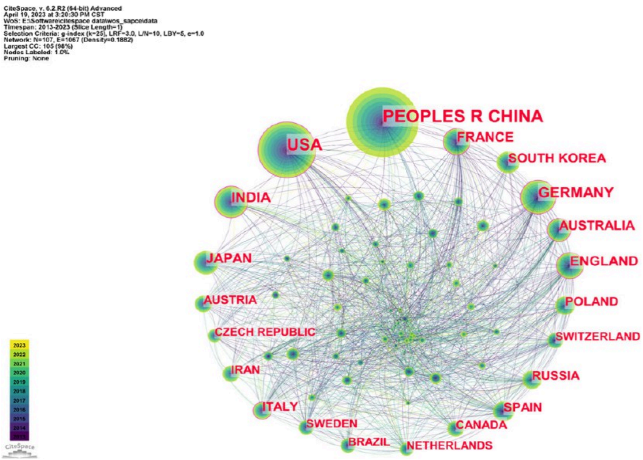

Figure 4. Knowledge map illustrating country cooperation networks.

depicts the node size as proportional to the volume of articles on nanoindentation technology published by each country or research institution. The connections between nodes illustrate collaborative relationships, with a higher number of connections indicating stronger cooperation among the entities. Additionally, the circles and lines are color-coded according to a year legend located in the lower left corner, which indicates the presence of countries or research institutions in each respective year. This study aims to analyze the collaboration network among these entities to identify key contributors to the literature on nanoindentation technology and to elucidate the nature of their collaborative relationships.

A total of 585 institutions across 107 countries or regions have published articles on nanoindentation technology. Visualization mapping of the country collaboration network reveals that the top three contributors in terms of publication volume are the People's Republic of China (4,844), the United States of America (USA; 3,161), and Germany (1,188). Scholars from these three nations have authored 9,193 articles, accounting for 63.96% of the total publications on nanoindentation between 2013 and 2022. Notably, the output from researchers in the People's Republic of China and the USA significantly surpasses that of other countries, underscoring their dominance in the research and application of nanoindentation technology. Interestingly, the top three countries globally, ranked by total national and regional gross domestic product (GDP), account for over half of the articles on this technology. This correlation suggests that adequate research funding may facilitate advancements in this field. Additionally, the analysis of the knowledge map of international collaboration indicates that the People's Republic of China is less connected to other nations compared to the USA and Germany. This implies that Chinese scholars focusing on nanoindentation technology tend to prioritize domestic collaborations. Therefore, it is recommended for these

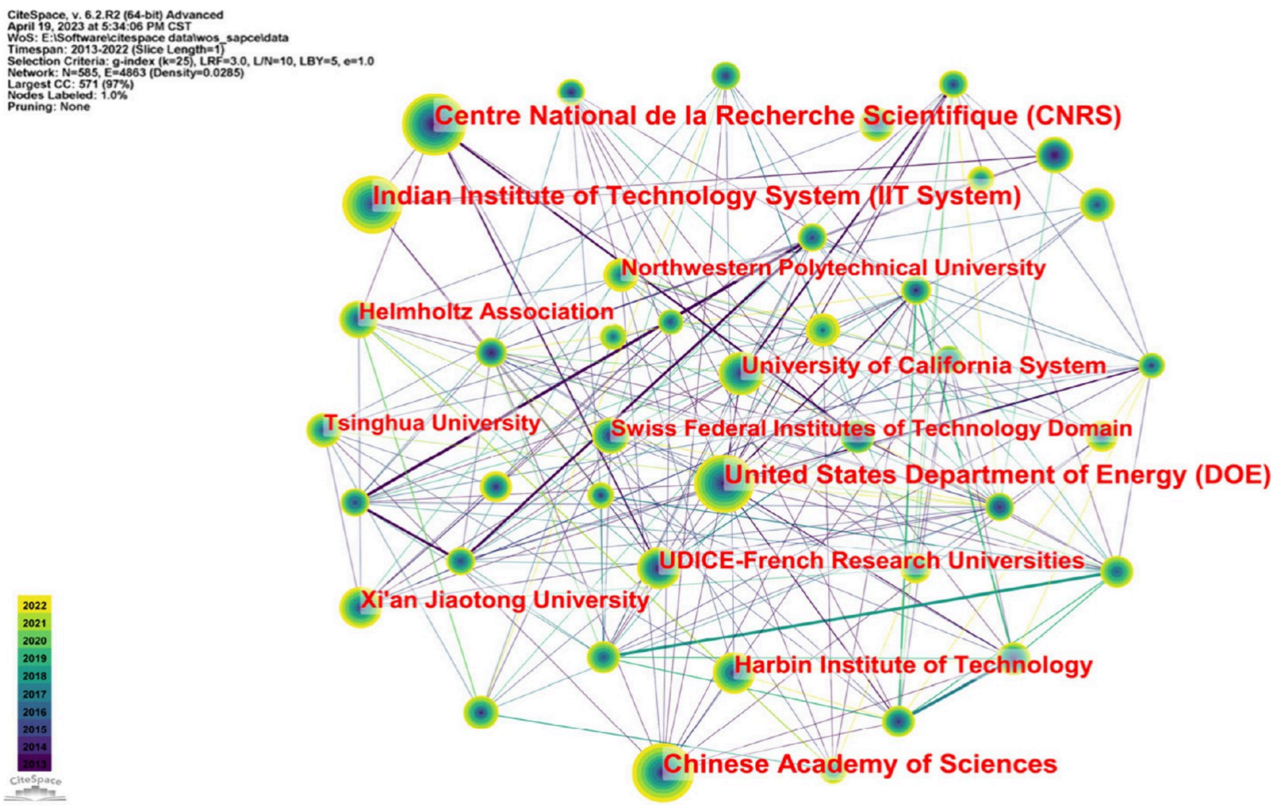

Figure 5. Knowledge map depicting research institutional collaboration networks.

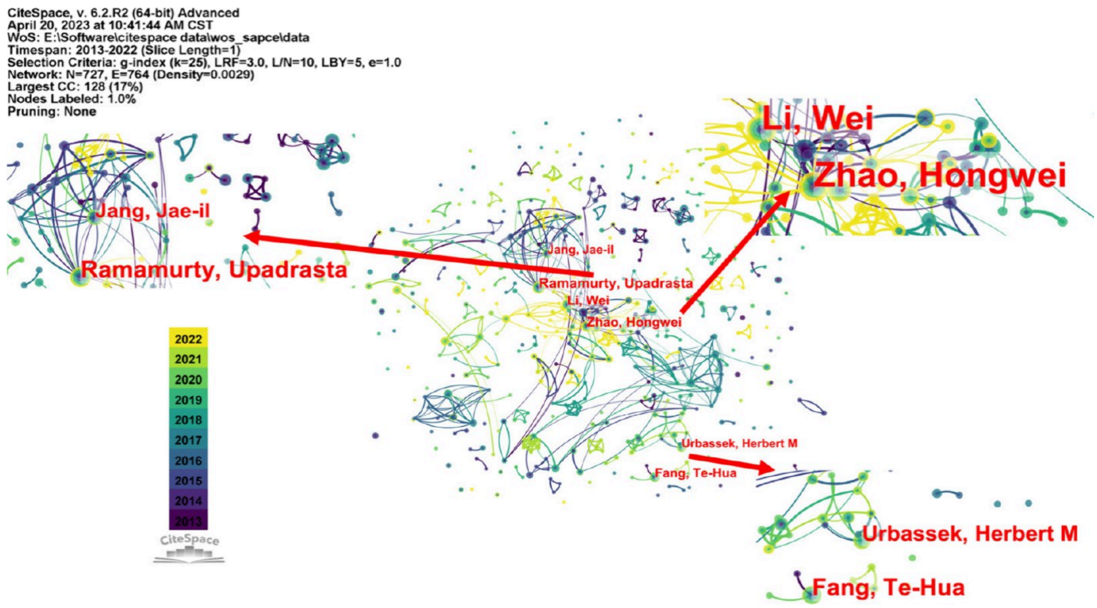

Figure 6. Knowledge map showing the collaboration networks among research scholars.

researchers to enhance their international collaborative efforts in future studies.

Furthermore, the knowledge map of research institutional collaboration networks reveals a cluster centered around prominent entities such as the United States Department of Energy (DOE), the University of California System, the Swiss Federal Institutes of Technology Domain, UDICE (Universités D'Institut de Recherche et de Formation en Économie)-French Research Universities, and the Chinese Academy of Sciences. These institutions exhibit close collaboration both within and across clusters. In terms of institutional publications, the leading research institutions in this field include the Chinese Academy of Sciences (470), the Centre National de la Recherche Scientifique (458), the Indian Institute of Technology System (IIT System) (447), and the United States DOE (446). Meanwhile, the research landscape for nanoindentation technology is predominantly centered around scientific research institutions, with key universities serving as supplementary resources. This concentration is attributed to the availability of adequate academic resources, exceptional research teams, and advanced research facilities. Moreover, there is a notable prevalence of coauthorships between research institutions and key universities, alongside increased collaboration among research universities and prominent institutions within the same country and region. Additionally, cross-country and regional partnerships are becoming prevalent. Research institutes worldwide play a critical role in advancing nanoindentation research and its applications. In addition, these organizations are distinguished by both intraregional collaborations with geographically proximate partners and a growing trend toward cooperation across different regions and countries.

In cooperation networks, centrality is a crucial parameter, reflecting the frequency with which a node functions as the shortest bridge between two other nodes. The betweenness centrality of a node increases as it serves more frequently as an intermediary. A high betweenness centrality indicates the importance of a node in shaping relationships. In an international context, the seven nations with a mediator centrality exceeding 0.1 are England (0.16), Germany (0.15), France (0.15), India (0.13), the USA (0.12), Australia (0.12), and Italy (0.11). Interestingly, despite having the highest number of publications, the People's Republic of China shows a mediated centrality of only 0.02. This suggests that although Chinese scholars have contributed extensively to the literature, they maintain relatively few international collaborations. Moreover, their research on the nanoindentation technique has primarily focused on applications with limited critical advancements, resulting in a reduced impact. Regarding institutions, countries with high publication volumes are associated with institutions exhibiting high intermediary centrality. For instance, the Chinese Academy of Sciences (0.05) in China, the United States DOE (0.08), and the Helmholtz Association (0.06) in Germany demonstrate this pattern. Notably, several prominent institutions in the United States, such as the University of California System (0.06), the State University System of Florida (0.08), and the Massachusetts Institute of Technology (MIT) (0.06), also display high intermediary centrality. These organizations are internationally renowned, and their articles attract considerable attention from a broader range of researchers and scholars.

3.1.3. Visualization and Analysis of Research Scholar Collaboration Networks. Visualizing and analyzing authors in the literature often provides a clear picture of the leaders in a specific field of scientific research. Assessing the research output of these academic leaders offers insights into the frontiers and trends in the discipline. By selecting the "Author" option in CiteSpace, a knowledge map illustrating the collaboration networks of research scholars can be generated. The results are depicted in Figure 6.

A total of 727 research scholars were identified as having published articles on nanoindentation from 2013 to 2022. All of these scholars had a minimum of three publications, with 25 scholars publishing 20 or more articles. Table 1 presents the top 21 scholars based on the publication count, along with their publication statistics, country/region, and institutional affiliations. The core authors of nanoindentation technology can be determined by establishing the minimum number of publications required for core authorship. Typically, this identification process emphasizes publications where authors are listed as first authors, including independent authors. A statistical analysis of

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Table 1. Twenty-One Scholars with the Highest Number of Publications

number	authors	counts	affiliations	countries/ regions
1	Upadrasta Ramamurty	66	Nanyang Technological University	Singapore
2	Hongwei Zhao	49	Jilin University	People's Republic of China
3	Wei Li	48	Nankai University	People's Republic of China
4	Te-Hua Fang	45	National Kaohsiung University of Science and Technology	People's Republic of China/ Taiwan
5	Jae-il Jang	34	Hanyang University	South Korea
6	Herbert M. Urbassek	31	University of Kaiserslautern	Germany
7	Xianghe Peng	29	Chongqing University	People's Republic of China
8	Takahito Ohmura	28	National Institute for Materials Science	Japan
9	Paul Munroe	28	University of New South Wales Sydney	Australia
10	Karsten Durst	28	Technical University of Darmstadt	Germany
11	Yi Ma	27	Zhejiang University of Technology	People's Republic of China
12	Hu Huang	25	Jilin University	People's Republic of China
13	Siqun Wang	25	The University of Tennessee	United States of America
14	David F. Bahr	24	Purdue University	United States of America
15	Tao Fu	24	Chongqing University	People's Republic of China
16	Manjima Bhattacharya	24	Indian Institute of Science Education and Research	India
17	P. Huang	24	Xi'an Jiaotong University	People's Republic of China
18	Wei Zhang	23	Jilin University	People's Republic of China
19	J. J. Roa	23	Polytechnic University of Catalonia	Spain
20	Fei Wang	23	Xi'an Jiaotong University	People's Republic of China
21	Arjun Dey	23	Central Glass and Ceramic Research Institute	India

authorship patterns in nanoindentation research literature in the Web of Science was conducted, utilizing Price's Law to assess the distribution patterns. The scholar with the highest number of publications is Upadrasta Ramamurty from Nanyang Technological University, Singapore, with a total of 66 publications over the decade. The minimum publication threshold for candidates to be considered core authors in nanoindentation research is as follows:

$$M_p = 0.749\sqrt{N_{max}} = 0.749 \times \sqrt{66} = 6.08 \quad (1)$$

According to Price's Law, when the proportion of papers authored by core authors exceeds approximately 50% of the total output, it infers the emergence of a core group within the research domain. Based on eq 1, authors with more than six publications are classified as core authors after rounding the results. Statistics from 2013 to 2022 indicate that 213 authors met this criterion, collectively publishing 2,516 documents, which represents 17.5% of the total selected documents. This suggests that a core group of authors has not yet developed in the field of nanoindentation technology.

The analysis of collaborative relationships among scholars reveals a scattered and distributed network resembling a sky full of stars. A limited number of scholars engage in close cooperation, while a higher density of node connectivity among these individuals fosters a more distinct research community, as illustrated in Figure 6. This phenomenon can be attributed to the limitations imposed by geographic boundaries, which typically lead to increased collaboration within the same country or region. Additionally, the application of nanoindentation technology across various fields results in lower collaboration rates among scholars from different research domains.

Following the analysis of prolific scholars in nanoindentation research, the subsequent step involved identifying key literature. Our focus was primarily on highly cited articles within the Web of Science database. Table 2 highlights the top ten most cited studies related to nanoindentation technology, as highly cited research indicates significant research hotspots during a specific period. Furthermore, these articles are typically published in high-quality journals widely recognized by scholars, which enhances their visibility and citation counts. Of these ten highly

Table 2. Top 10 Highly Cited Papers on Nanoindentation Technology

number	title	author	journal	citation count	year
1	An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments	W.C. Oliver and G.M. Pharr	Journal of Materials Research	21 078	1992
2	Measurement of the elastic properties and intrinsic strength of monolayer graphene	Changgu Lee et al.	Science	18 769	2008
3	Large Scale Growth and Characterization of Atomic Hexagonal Boron Nitride Layers	Li Song et al.	Nano Letters	2400	2010
4	Sample dimensions influence strength and crystal plasticity	Michael D. Uchic et al.	Science	2101	2004
5	Overview of constitutive laws, kinematics, homogenization and multiscale methods in crystal plasticity finite-element modeling: Theory, experiments, applications	Franz Roters et al.	Acta Materialia	1554	2010
6	A buckling-based metrology for measuring the elastic moduli of polymeric thin films	Christopher M. Stafford et al.	Nature Materials	1375	2004
7	Characterization of polydimethylsiloxane (PDMS) properties for biomedical micro/nanosystems	Alvaro Mata et al.	Biomedical Microdevices	1130	2005
8	Atomistic mechanisms and dynamics of adhesion, nanoindentation, and fracture	Uzi Landman et al.	Science	1016	1990
9	Dislocation processes in the deformation of nanocrystalline aluminum by molecular-dynamics simulation	Vesselin Yamakov et al.	Nature Materials	990	2002
10	Mechanical properties of ultrahigh-strength gold nanowires	Bin Wu et al.	Nature Materials	961	2005

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Figure 7. Ten most cited publications on the topic of nanoindentation.

cited documents, one is a review article, while the remaining nine are original research articles. The most cited article, *"An improved technique for determining hardness and modulus of elasticity using load and displacement sensing indentation experiments"* by W.C. Oliver and G.M. Pharr, introduces an advanced method for nanoindentation,[36] which has established a foundation for subsequent research and has amassed a total of 21,078 citations. Another significant contribution ranked fifth, is a review article that explores the continuum-based variational formulation for describing the elasto-plastic deformation of anisotropic nonhomogeneous crystalline materials, with a particular emphasis on the crystal plasticity finite element model. Additionally, it compares the model's predictions with findings from nanoindentation experiments.[50] Articles No. 2, No. 3, No. 6, No. 7, and No. 10 focus on the experimental application of nanoindentation techniques across various materials.[25,26,51−53] The substantial number of citations for these studies likely reflects the significant interest in the materials investigated or the pioneering application of nanoindentation in these contexts. Articles No. 1, No. 4, No. 8, and No. 9 contribute significant theoretical advancements in the field of nanoindentation.[54−56] These highly cited works play a crucial role in the development of nanoindentation technology, which explains their substantial citation frequency.

3.1.4. Analysis of Literature Source Journals. To investigate the topic of nanoindentation, a search was performed for relevant articles in the Web of Science database. Subsequently, "Publication/Source Titles" were selected from the search results page to generate a ranking of journal articles centered on nanoindentation. The top ten journals are shown in Figure 7, while Table 3 outlines the journal publishers and their respective impact factors. Furthermore, Figure 8 illustrates the keyword discipline co-occurrence knowledge map. Collectively, this suggests that material science is the predominant research direction in nanoindentation technology, which aligns with our expectations. However, it is crucial to recognize that the applications extend beyond this discipline, including fields such as physics, chemistry, cell biology, mechanics, and other research areas. There is potential for nanoindentation technology to be applied in a broader range of disciplines, facilitating significant advancements. Consequently, the development of theoretical models tailored to various fields is likely to become the next focal point in nanoindentation research.

Table 3. Publishers and Impact Factors of the Top 10 Publications

number	journal	counts	impact factor (2022)	Publishers
1	Surface and Coatings Technology	1107	5.4	Elsevier
2	Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing	872	6.4	Elsevier
3	Journal of Alloys and Compounds	616	6.2	Elsevier
4	Acta Materialia	525	9.4	Elsevier
5	Applied Surface Science	465	6.7	Elsevier
6	Surface and Coatings Technology	443	5.4	Elsevier
7	Thin Solid Films	442	2.1	Elsevier
8	Ceramics International	438	5.2	Elsevier
9	Journal of Materials Research	436	2.7	Springer
10	Materials	402	8.4	MDPI

3.2. Application Analysis of Nanoindentation Technology. *3.2.1. Advances in Nanoindentation Technology Applied to Various Materials.* Since its inception, nanoindentation has been utilized for homogeneous materials, including metals,[57−59] coatings,[60−62] films,[63−65] crystals[66−68] and glass.[69−71] Over time, its application has expanded to encompass multiphase inhomogeneous materials such as wood,[72−74] bone,[75−77] arterial blood vessels,[78] cementitious materials,[79−81] coal,[82−84] and rocks.[85−87] For multiphase homogeneous materials, nanoindentation facilitates the measurement of mechanical properties at the nanoscale, providing insights into load−displacement curves, modulus of elasticity, hardness, fracture toughness, strain-hardening effects, viscoelasticity, and creep behavior. In contrast, multiphase inhomogeneous materials exhibit spatial inhomogeneity at the micro and nanoscales. The mechanical and technical properties of multiphase inhomogeneous materials are characterized by the specific geometrical dimensions and mechanical parameters of their structural components.[88] In materials science and rock mechanics, nanoindentation testing can yield valuable insights into the distribution and mechanical properties of different phases, thereby enhancing the understanding of the mechanical behavior of these materials. In nanoindentation tests conducted

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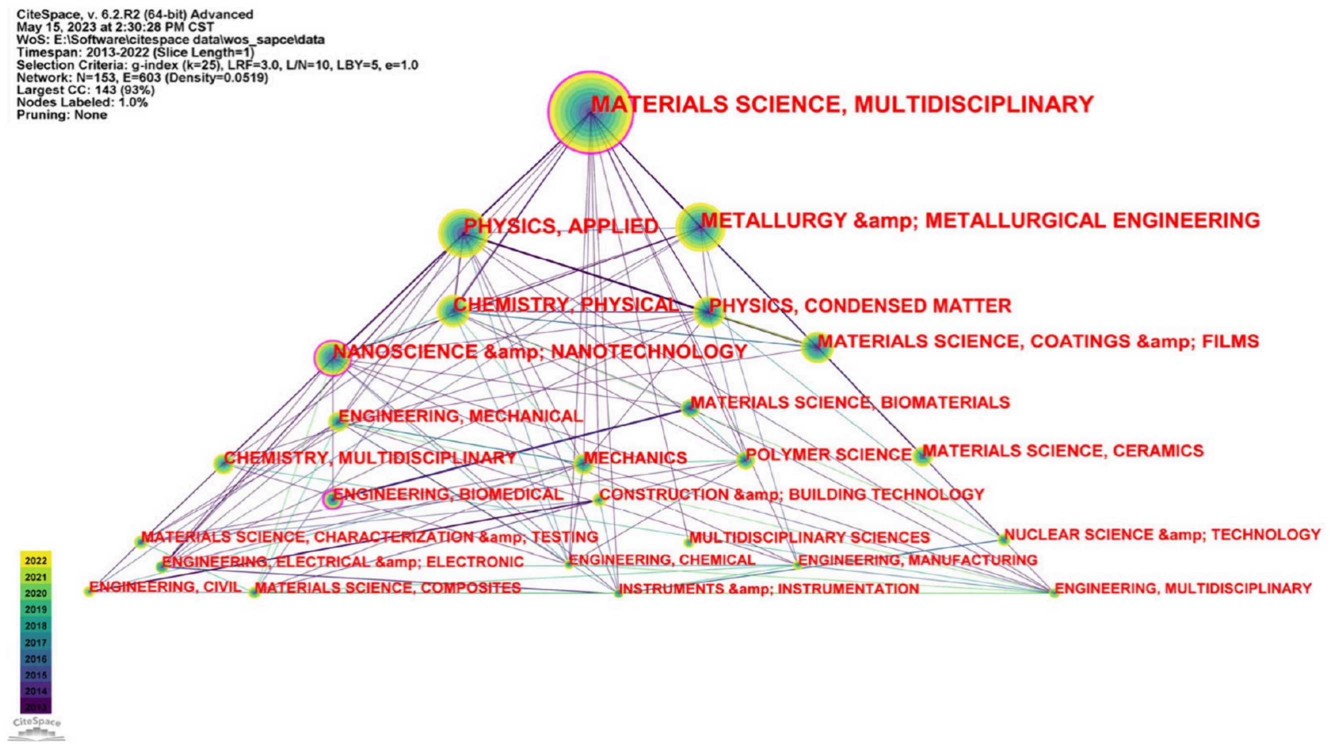

Figure 8. Knowledge map depicting the co-occurrence of keywords across disciplines.

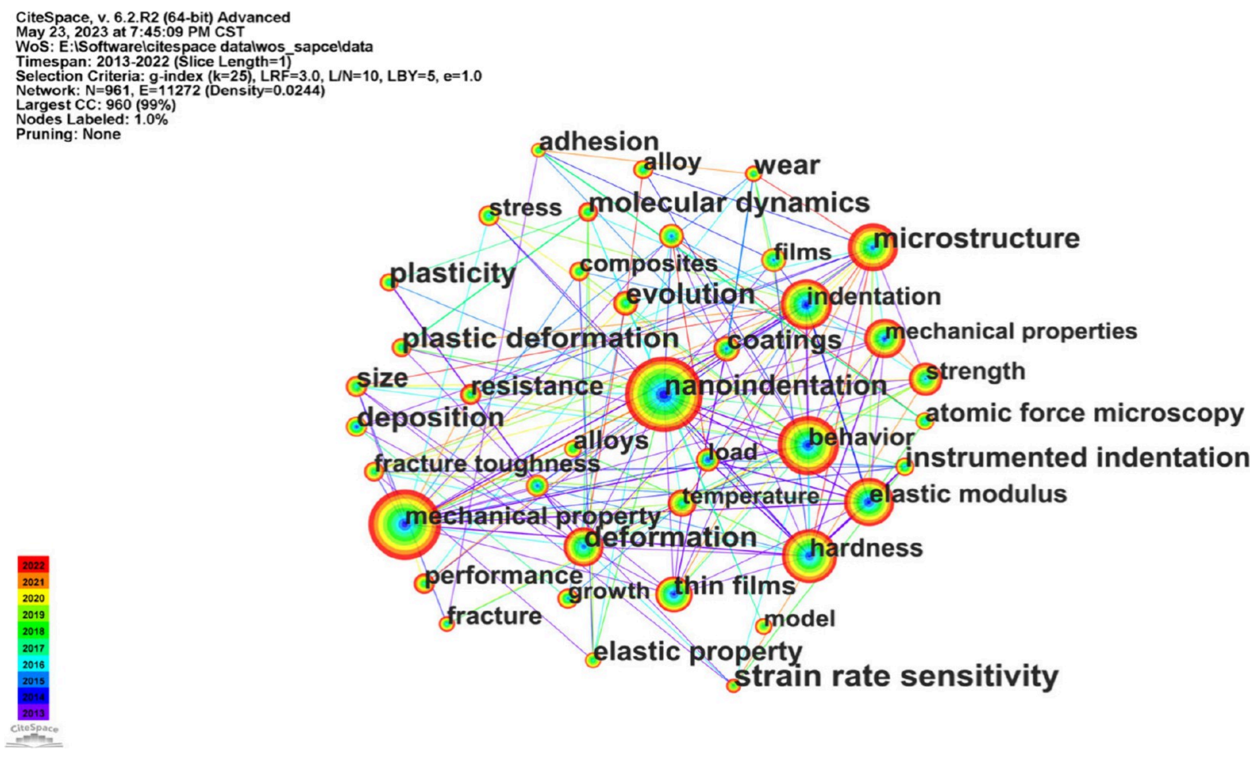

Figure 9. Knowledge map illustrating keyword co-occurrence.

following the Oliver-Pharr method, a perfectly flat surface is assumed for the sample, which implies that the indentation tests exhibit self-similarity. For homogeneous materials, the outcome of a single indentation is determined solely by the indentation depth. Conversely, for nonhomogeneous materials, the accuracy of nanoindentation is affected by surface roughness, with excessive roughness compromising the self-similarity of the indentation test.[80] Studies by Bobji et al.[89] and Kim et al.[90] demonstrate that increased surface roughness leads to greater data dispersion, thereby impacting test results. Consequently, when performing nanoindentation on nonhomogeneous materials, surface polishing is crucial. A smooth surface minimizes the influence of the sample on the test outcomes, enhancing the repeatability and reliability of the results.

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Table 4. Top 15 Keywords and Frequency of Occurrence

no.	keyword	counts	no.	keyword	counts	no.	keyword	counts
1	nanoindentation	4345	6	elastic modulus	2052	11	strength	1018
2	mechanical property	3877	7	microstructure	1957	12	temperature	805
3	behavior	2796	8	deformation	1436	13	films	705
4	hardness	2592	9	mechanical properties	1392	14	coatings	695
5	indentation	2099	10	thin films	1172	15	modulus	662

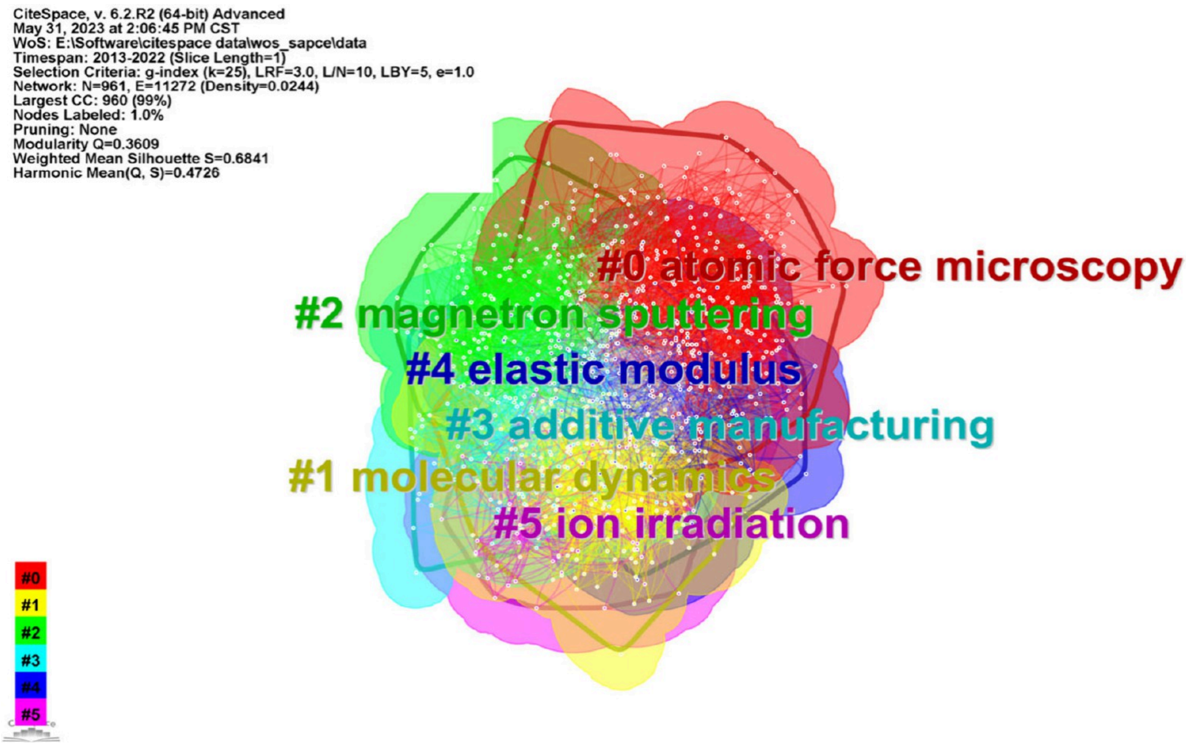

Figure 10. Knowledge map illustrating keyword clustering.

3.2.2. Keyword Co-occurrence Visualization Analysis. Keywords play a crucial role in academic articles by providing a concise and general overview of the content. A keyword co-occurrence network, constructed through the co-occurrence of keywords, helps to identify and extract research hotspots that have garnered significant attention from scholars, particularly in the field of nanoindentation technology. In CiteSpace, setting the node type to "Keyword" facilitates the generation of a keyword co-occurrence knowledge map, as illustrated in Figure 9.

Meanwhile, the network in Figure 9 consists of 961 nodes and 11,272 links, with a scale factor g-index $k = 25$. The size of each node corresponds to the frequency of keywords, with larger nodes indicating higher keyword frequency during the specified period. The connections between nodes represent the co-occurrence of these keywords at a particular time.

Table 4 presents the 15 most frequently occurring keywords, with 11 of them appearing more than 1,000 times, indicating their prominence in the materials discipline. The top three keywords are "nanoindentation", "mechanical property" and "behavior" with frequencies of 4,345, 3,877, and 2,796, respectively. This suggests that nanoindentation is a crucial method for investigating the mechanical properties and behavior of materials.

3.2.3. Keywords Clustering Visualization Analysis. Keyword clustering is a fundamental method for further exploring research hotspots within scientific fields. A keyword clustering map, constructed using keyword co-occurrence, was generated with the assistance of CiteSpace, as illustrated in Figure 10.

In the analysis, the module value ($Q = 0.3609$) exceeds 0.3, and the average profile value ($S = 0.6841$) is greater than 0.5 and approaches 0.7, indicating that the keyword clustering map is reasonably reliable.[40,91]

A total of six main clusters were derived using the Log Likelihood Ratio algorithm, shedding light on key research areas in nanoindentation technology. These clusters include AFM, molecular dynamics (MD), magnetron sputtering, additive manufacturing (AM), elastic modulus, and ion irradiation.

- Cluster #0: Atomic force microscopy. AFM is a novel instrument that represents a cutting-edge instrument with atomic-level resolution, surpassing that of the scanning tunneling microscope (STM).[92] While AFM was developed from the principles of STM, it utilizes van der Waals force interactions to examine the surface properties at the atomic scale. Typically, AFM is employed in conjunction with nanoindentation techniques for the precise quantification of indentation.[92,93]
- Cluster #1: Molecular dynamics. MD simulation has become a widely used method for studying molecular systems, with significant advancements in recent years. Grounded in classical mechanics, quantum mechanics, and statistical mechanics, this approach utilizes computer-

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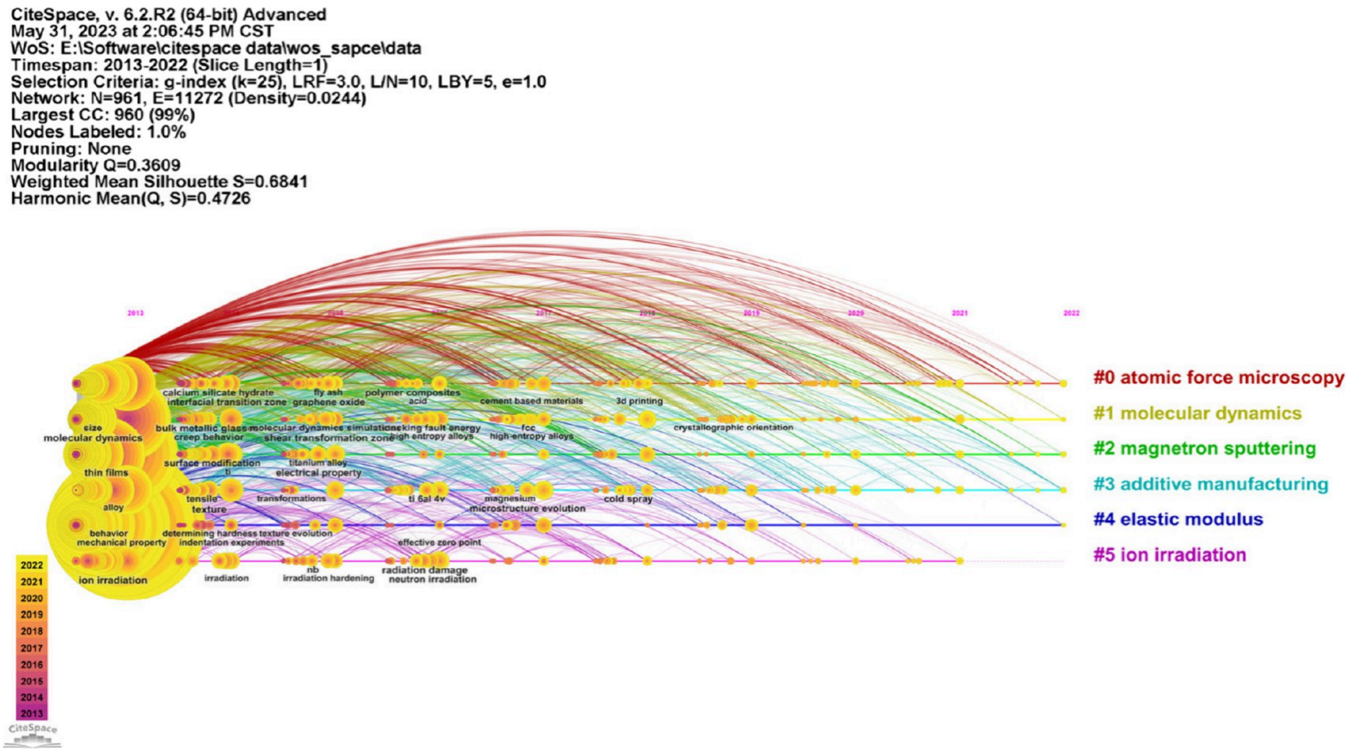

Figure 11. Knowledge graph showing keyword clustering over time.

based numerical solutions to solve the equations of motion for molecular systems, enabling the investigation of their structure and properties. As a third major scientific approach, complementing experimental and theoretical methods, MD simulations have found widespread applications in various fields, including chemistry, chemical engineering, materials science, engineering physics, and biomedicine. In nanoindentation experiments, MD simulations are particularly valuable for examining the effects of parameters such as indenter shape and indentation speed, significantly enhancing the experimental outcomes.[94−98]

- Cluster #2: Magnetron sputtering. Magnetron sputtering is a type of Physical Vapor Deposition (PVD) that relies on the interaction between magnetic and electric fields. This interaction causes electrons to circulate near the target surface, thereby increasing the likelihood of argon ionization through electron impact. The resulting ions, driven by the electric field, are directed toward the target surface, leading to the sputtering of the target material. This technique is commonly employed to prepare coatings and thin films on various substrates, with nanoindentation subsequently used to assess their mechanical properties.[99−102]
- Cluster #3: Additive manufacturing. AM utilizes the gradual accumulation of materials to create solid parts. This method enables the rapid and precise production of components with complex geometries using a single machine, eliminating the need for traditional tools, fixtures, and multiple machining processes. AM effectively addresses the challenge of fabricating intricate structural components while significantly reducing the number of machining processes and shortening production times, thereby realizing the concept of "free manufacturing". The advantages of AM are particularly evident as the complexity of product structures increases. Recently, there has been growing interest in AM from governments, research institutions, and industries. Additionally, nanoindentation has emerged as a promising technique for evaluating the micromechanical properties of materials produced via AM.[103−108]
- Cluster #4: Elastic modulus. Elastic modulus is a critical property of engineering materials. From a macroscopic perspective, it represents an object's capacity to resist elastic deformation, while on a microscopic level, it reflects the bonding strength between atoms, ions, or molecules. The nanoindentation technique enables the acquisition of the load−displacement curve of a material's surface, allowing for the calculation of its elastic modulus. Thus, nanoindentation serves as a vital method for measuring the elastic modulus of materials at the micro/nanoscale.[109−112]
- Cluster #5: Ion irradiation. Ion irradiation technology represents a significant branch of modern materials science. This technique employs a targeted ion beam to conduct controlled modifications, enhancements, and repairs to the surface or interior of a material, thereby altering its physical, chemical, and electrical properties. Modifying materials to enhance their properties has been a longstanding research focus in this field. After ion irradiation, changes in mechanical properties can be examined using nanoindentation techniques.[113−118]

Using keyword co-occurrence analysis, the Timeline View module in CiteSpace was utilized to generate a keyword clustering evolution map, as illustrated in Figure 11. This timeline map provides an extended overview of the keywords within the clusters over time. Notably, clusters #0, #1, #2, #3, #4, and #5 first appeared in 2013, reflecting the fact that the literature downloaded for this analysis began in that year and the close relationship of the cluster keywords with nanoindentation. Regarding node distribution, the literature production for clusters #0, #1, #2, #3, and #4 has shown steady growth, while cluster #5 has experienced minimal follow-through and a decline in attention since 2021.

Overall, nanoindentation is a pivotal material characterization technique, with its research focus evolving in tandem with advancements in material technology. Whether dealing with homogeneous or nonhomogeneous materials, nanoindentation remains indispensable to societal development. As science and technology advance, materials scientists are presented with an increasing array of methods for modulating material properties. Consequently, nanoindentation has also progressed, emerging as an important tool for correlating macroscopic mechanical properties with the microstructure of various materials. This evolution has led to shifting research priorities, with the overarching goal of enhancing the characterization of mechanical properties.

3.2.4. Analysis of Keywords with the Strongest Citation Bursts. Keywords exhibiting strong citation bursts can unexpectedly rise in prominence at certain points. By extracting these keywords, researchers can pinpoint recent and future trends within a given subject area. The burst detection algorithm detects terms with a high-frequency change rate among a large set of subject-related words, thus identifying burst terms.[119,118] A stronger keyword emergence indicates a higher level of influence, while an earlier start year of the associated keywords suggests that this direction has garnered scholarly attention sooner. Figure 12 presents a keyword burst time analysis diagram. In this figure, "Year" denotes the year of the keyword's first appearance, "Begin" marks the starting year of the corresponding keyword's emergence, and "End" indicates the concluding year. The dark blue segment illustrates the duration of the keyword's presence, while the red segment signifies the period of its significant growth.

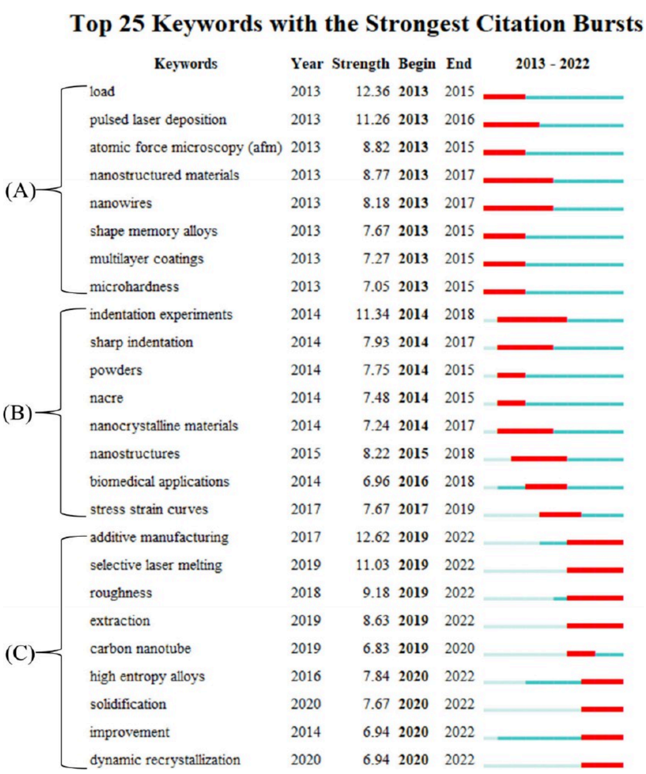

Figure 12. Diagram of keyword burst time analysis.

In terms of strength and load, techniques such as pulsed laser deposition (PLD), indentation experiments, AM, and selective laser melting demonstrate notable significance. The research frontier of nanoindentation technology can be categorized into three phases. Phase A, which commenced in 2013, features keywords such as load and PLD as the leading frontiers. Phase B serves as a transitional phase, primarily characterized by indentation experiments. Currently, we are in Phase C, which is predominantly led by AM and selective laser melting.

Recent research has concentrated on eight cutting-edge topics related to nanoindentation technology, including AM, selective laser melting, surface roughness, material extraction, high entropy alloys, solidification processes, performance improvement, and dynamic recrystallization. Notably, AM and selective laser melting stand out as the most prominent topics, achieving strengths of 12.62 and 11.03, respectively, thereby ranking among the top five of the 25 identified keywords.

In general, the analysis should prioritize periods where the conclusion of one burst overlaps with the beginning of another. For instance, microhardness in phase A coincides with the burst of indentation experiments in phase B, while the stress−strain curves in phase B overlap with AM in phase C. This phenomenon reflects a shift in the research focus during the transitions among these phases. Among the 25 keywords analyzed, AM exhibited the highest prominence. It first emerged in 2017, surged in popularity in 2019, and continues to gain traction in current research. Therefore, this technology is increasingly acknowledged and utilized by researchers worldwide. As previously mentioned, nanoindentation can assess the micromechanical properties of materials produced via AM, thereby underscoring the keyword's significant emergence and sustained relevance in the field.

3.3. Discussion. Nanoindentation, a method for quantitatively characterizing the mechanical properties of materials at the micro/nanoscale, has garnered significant interest from materials scientists across diverse fields since its inception. The evolution from traditional indentation to nanoindentation has opened new avenues for assessing material properties more effectively. This study analyses 14,373 pieces of literature on nanoindentation research published between 2013 and 2022 and provides a historical overview of the development of indentation technology. Moreover, it presents a quantitative and visual review of scholarship and advancements in this field using CiteSpace. The objective is to offer insights that will facilitate future developments by systematically examining the evolution of nanoindentation techniques. The findings of the study are as follows:

(1) The analysis of time-series characteristics of the annual number of publications on nanoindentation technology, alongside knowledge maps illustrating country cooperation networks, research institutional collaboration networks, research scholar collaboration networks, and keyword visualization mapping, indicates a gradual development in this field. With the increasing application of nanoindentation technology, the theoretical understanding of its principles is also advancing and becoming more comprehensive.

(2) The analysis of time-series characteristics of annual publication numbers reveals a gradual upward trend from 2013 to 2020. In contrast, the total number of

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articles addressing nanoindentation techniques remains relatively modest compared to the literature on traditional material characterization methods, such as STM (Scanning Tunneling Microscope) and AFM. This disparity arises from the narrower scope and visibility of nanoindentation in relation to other characterization techniques. Nevertheless, as nanoindentation technology continues to develop, its range of applications is expanding. Furthermore, the integration of nanoindentation with real-time electronic imaging is expected to encourage more scholars to adopt this methodology. Consequently, an increase in publications related to nanoindentation technology is anticipated.

(3) Analyzing the knowledge maps of country cooperation networks, research institutional collaboration networks, and research scholar collaboration networks suggests that articles on nanoindentation demonstrate stronger collaboration among institutions and researchers within the same country, while international collaboration remains comparatively limited. Additionally, the top three nations in publication volume also rank highest in total GDP, indicating that sufficient research funding positively impacts the advancement of this technology. From the perspective of research scholars, the field of nanoindentation technology has yet to establish a core group of authors, resulting in a fragmented collaborative network among scholars. Notably, while China leads in a number of publications, it exhibits lower intermediary centrality. This implies that Chinese scholars should focus on strengthening their collaborative efforts to enhance the country's international influence, even as publication volume continues to rise.

(4) Keyword visualization mapping reveals that nanoindentation serves as a crucial tool for characterizing the mechanical properties of materials at micro and nanoscales. The knowledge map of keyword clustering indicates a close association between nanoindentation and five keyword clusters. Furthermore, the keyword burst time analysis categorizes the evolution of nanoindentation technology from 2013 to 2022 into three distinct phases, with a current emphasis being on phase C. Notably, AM has emerged as the most prominent area, exhibiting a strength of 12.62, which signifies a significant surge in interest. This trend reflects an increasing preference among researchers for this technology. Additionally, there is a growing inclination among academics to employ nanoindentation techniques to test the micromechanical properties of components produced through AM.

4. CONCLUSIONS

This study employs CiteSpace to visualize and analyze articles related to nanoindentation, providing a novel perspective for summarizing and reviewing the advancements in this technology. This approach facilitates the exploration of future research directions in the field. The following conclusions can be drawn from this study:

(1) The application of nanoindentation techniques for material characterization relies on the assumption that the material behaves as a stress-free, single-phase homogeneous continuum. While numerous scholars have employed nanoindentation to multiphase inhomogeneous materials, such as cement, significant challenges persist in these challenges. Future research will concentrate on optimizing the use of nanoindentation techniques for such materials. Current methodologies remain inadequate for various material types, highlighting the need for the development of new theories and methods specifically tailored to address these challenges, which may serve as promising avenues for advancing this technology.

(2) The Oliver-Pharr method is currently the most widely used technique for nanoindentation. However, this approach relies solely on the load−displacement curve to represent the mechanical characteristics of materials, which may not fully capture the properties of certain materials. Consequently, it is essential to consider additional factors beyond the load−displacement curve when employing nanoindentation technology. By integrating other material characterization techniques, such as AFM and STM, it becomes possible to examine the indentation morphology simultaneously, enabling a more comprehensive characterization of the material's mechanical properties from multiple perspectives.

(3) Another aspect that hinders the development of nanoindentation technology is its testing range, which includes factors such as temperature, humidity, and indentation speed. For certain materials, variations in temperature and humidity, along with the speed at which the indenter penetrates the material, can significantly influence the results. While some studies have investigated nanoindentation testing in extreme temperature environments, standardized testing criteria have not yet been established. Consequently, further development and enhancement in this area of nanoindentation technology are essential.

(4) A prerequisite for the application of nanoindentation is that the surface of the material must be smooth and flat, which necessitates sanding and polishing prior to testing. An essential aspect of this process involves investigating the effects of polishing on the material. Specifically, it is necessary to ascertain whether the mechanical properties of the polished material are representative of the entire material and to quantitatively characterize the impact of material roughness on the nanoindentation results.

(5) The measurement accuracy of nanoindentation techniques poses a significant challenge for researchers. Numerous factors can influence this accuracy, making it crucial to systematically address these factors to minimize their impact. Additionally, exploring the integration of nanoindentation with complementary technologies to enhance measurement precision represents critical areas for future research.

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Notes

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