Evolution Characteristics of Advanced Nonferrous Metal Industry Patent Cooperation Network in China from the Perspective of Multilayer Network

Qingxiao Wang and Wenqian Zhu
Henan University of Science and Technology, Luoyang 471023, China
Correspondence should be addressed to Qingxiao Wang; wqx@haust.edu.cn
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The advanced nonferrous metal industry is a national strategic emerging industry, and its innovation ability is crucial to the transformation and development of downstream industries such as aerospace, rail transit, electronic information, and automobiles to the high end of the industrial value chain. The research on the evolution characteristics of its cooperative network is beneficial to the research on the mechanism of improving the innovation capability of the industry. Based on the cooperative invention patent application data in 2002–2020, using the social network analysis method and Gephi 0.9.2 visualization to construct a patent cooperation network and knowledge network, this paper analyzes the overall characteristics and evolution law of the patent cooperation network in the advanced nonferrous metal industry. It is found that, first, the structure of the innovation network in China’s advanced nonferrous metals industry is becoming more and more complex. The scale of the cooperation network and knowledge network is increasing, and the small world is obvious. Second, some innovation subjects, as key nodes, play the role of “bridge” and grasp the general direction of technology. The structure of the key nodes in the network has changed, and the cooperative innovation network of industry-university-research has gradually evolved from enterprise-led to university-led. Third, the number of technical categories has increased and the depth of technology has been enhanced in China’s advanced nonferrous metal field. Hot technical fields are characterized by high intensity, wide range, and stable advancement. Based on the research findings, some suggestions and enlightenment are put forward to promote the development of the advanced nonferrous metal industry.

1. Introduction
The advanced nonferrous metal industry is one of the strategic emerging industries. Developing an advanced nonferrous metal industry not only helps to promote the adjustment of China’s current economic structure and the upgrading of industrial structures but also deeply affects the effectiveness of building an innovative country in China. In recent years, the Chinese government has given great policy support to the advanced nonferrous metal industry. China’s advanced nonferrous metal industry has made rapid development and great progress, but there is still a big gap compared with international giants in the core technology field of the industry.

The patent is an important means of technological innovation and achievement transmission and exchange, and it is also an important index to judge the degree of technological innovation. Patents have an important impact on the development and technological breakthroughs of related industries. Patent innovation is the driving force of technological development, which is mainly reflected in optimizing patent layout, promoting technological innovation, and realizing industrial applications. The development of the modern manufacturing industry cannot be separated from cooperative innovation, and the need for cooperative innovation in the advanced nonferrous metal industry is more prominent. Patent cooperation is an important form of cooperative innovation, which can provide important
innovation power for the development of enterprises. By studying the patent innovation network, we can understand the development trend of technological innovation, the layout characteristics, and the evolution laws of patents in China's advanced nonferrous metal industry. The innovation and development status of advanced nonferrous metals can be scientifically analyzed and reasonable suggestions can be put forward.

In recent years, more and more nonferrous metal manufacturing enterprises have cooperated with universities and research institutes in R & D and have jointly applied for patents on the background of emerging and cross-integrated new technologies. They spontaneously form a patent cooperation network, which can realize resource sharing and complementary advantages. This kind of patent cooperation network can greatly reduce the innovation cost and risk and improve the technological innovation ability of an industry. However, at present, the exploration and utilization of patent cooperation networks in China’s nonferrous metal manufacturing industry are far from enough, and the innovation and aggregation effect of patent cooperation networks have not been fully exerted. Thus, exploring, utilizing, and optimizing patent cooperation networks to improve industrial technological innovation ability has become an important way for China’s advanced nonferrous metal industry to shorten the technological gap between China and international oligarchs and break the technological blockade. With the development of China’s advanced nonferrous metal industry, the innovation network of China’s advanced nonferrous metal industry, including the knowledge network and cooperation network, has changed significantly and become more complex. So, what are the evolution characteristics of the patent cooperation networks and knowledge networks in China’s advanced nonferrous metal industry? In the evolution process of a cooperative network of advanced nonferrous metals, which enterprises and research institutions are the key nodes to grasp the general direction of technology and how do their composition structures change? What are the distribution of technology fields and the evolution law of technology hot fields in China’s advanced nonferrous metal industry? These are the problems worth studying. The purpose of this study is to reveal the evolution law of its structural characteristics by constructing the innovation network of China’s advanced nonferrous metal industry and to provide suggestions for optimizing the innovation network and strengthening technological innovation.

2. Literature Review

2.1. Research on Multilayer Innovation Network. Wang et al. pointed out that enterprise innovation is double embedded in the knowledge network composed of knowledge elements and the social network formed by the cooperative relationships of R & D personnel, and these two networks are decoupled [1]. The process of combining knowledge elements is the production process of innovation behavior [2], and all knowledge elements are connected in the process of combination, forming a knowledge network [3]. Innovation is actually the interaction process of the innovation subject’s knowledge base and the combination mode, and the structural characteristics of the knowledge network represent the combination potential of core knowledge fields [4], which in turn becomes an important factor affecting the innovation performance of enterprises.

From the perspective of social attributes of innovation activities, enterprises embedded in cooperative networks can provide favorable resources for enterprise innovation. The innovative behavior of enterprises needs to be realized through the process of expanding and deepening the specific social network [5]. It is found that enterprises in different positions in the network have different degrees of control over resources and information. Cooperative network structure and relationship characteristics will have a certain impact on cooperative innovation behavior and performance, resulting in nonequilibrium behavior of innovation subjects [6, 7] and differences in innovation performance [8]. In fact, the innovation activities of enterprises are multidimensional. The knowledge network and cooperation network in which R & D personnel are located have their own unique operational characteristics, which will have different impacts on innovation activities. At present, most of the research on the evolution characteristics of innovation cooperation is based on patent data to analyze its evolution characteristics or patterns from a single network level.

2.2. Research on the Evolution of Innovation Network. In terms of innovation network evolution, existing scholars mainly conduct research from three aspects. First, focus on the cooperative relationship between universities and research institutes, and explore the evolution of cooperative networks at different stages through the cooperative publication of papers and works. For example, Balconi et al. [9] analyzed the role of university professors in the Italian inventor patent cooperation network; Lissoni [10] found that universities occupy a core position in the patent cooperation network and have a stable cooperative relationship with other types of inventors; Li et al. [11] found that comprehensive universities, science and engineering universities, and energy-based enterprises occupy the core position in the school-enterprise patent cooperation network. The second is to study the evolution of the innovation network of strategic emerging technology industries, involving information foundations, intelligent manufacturing, biomedicine, and other industries. For example, Zhang et al. [12] from the software service industry, Cao et al. [13] from the new energy automobile industry, Li et al. [14] from the satellite and application industry, and Chen et al. [15] from the chip industry, respectively, confirmed this point. These research fields belong to national strategic emerging industries. The research on these strategic emerging industries is helpful in improving the comprehensive innovation level of China. But unfortunately, these studies have not involved the advanced nonferrous metal industry. The third is to study the structure and evolution of the regional patent cooperation network. For example, Ejermo and Karlsson [16] believed that geographic distance is a key factor affecting patent cooperation...
networks, and there is generally a phenomenon of intra-regional aggregation in patent cooperation networks. Pan et al. [17] studied the patent cooperation networks in 31 provinces of China and found that geographical distance would have an impact on the linkage of patent cooperation networks. However, other scholars put forward different views. For example, Wilhelmsson [18] found that cities with denser populations and more diverse industrial structures tended to have lower levels of patent cooperation; Zheng et al. [19] constructed the cross-city patent cooperation network of Fujian, Xiamen, and Quanzhou, measured the order of network evolution by using the concept of "entropy," and found that the cross-city cooperation network showed an obvious entropy increase in the evolution process.

2.3. Research on the Innovation Network of the Nonferrous Metals Industry. The advanced nonferrous metal industry is a national strategic leading industry and an important part of new materials. Its innovation ability is crucial to the transformation and development of downstream industries such as aerospace, rail transit, electronic information, and automobiles to the high end of the industrial value chain, so it is worth studying. Concerning the research of the advanced nonferrous metal industry, some scholars study the path of industrial development and innovation. Tian [20] proposed to strengthen the innovation capacity building of the industry, strengthen the knowledge alliance and technology alliance, and realize the integration of technology and management. Choose the path of independent innovation, enhance competitiveness by participating in international market resources, and improve the efficiency of the nonferrous metal industry. Lin et al. [21] combined the exploratory single case study method and studied the path of both exploratory innovation and utilization innovation in the process transformation of typical research institutes in the rare metal industry. It is found that the engineering center has become the key link in the transformation from exploratory innovation to utilization innovation. Research on the nonferrous metals innovation network. Zhou et al. [22] combined chaos theory to expound on the chaotic characteristics of the innovation network of nonferrous metal industry clusters. Too strong or too weak aggregation capability level of integrated units is not conducive to the development of a nonferrous metal cluster innovation network. In the development process of a cluster innovation network, it is necessary to adjust the evolution speed of the cluster innovation network by the strength of its aggregation ability. It is proposed that nonferrous metal cluster enterprises can be divided into four stages: generation, growth, maturity, and decline in the life cycle of the cluster innovation network. The above research on the advanced nonferrous metal industry provides a useful reference for this study.

"Triple Helix" innovation theory is an innovation theory established by Etzkowitz and Leydesdorff in 1995 [23]. The "Triple Helix" theory borrows the concept of biology and puts forward that all three parties can be the main body of innovation, and that the three parties cooperate and interact closely in innovation. At present, the “Triple Helix" innovation theory has been widely used in academic circles to evaluate the collaborative interaction and dynamic evolution of universities, industries, and governments (including scientific research institutions) [24]. Many scholars have introduced the "Triple Helix" theory into the innovation network research of industry, education, and research [25, 26].

Therefore, based on the “Triple Helix” theory, enterprises, universities, and research institutes can be regarded as three types of innovation subjects, with the support of the government and other relevant institutions, and carry out innovation cooperation activities based on a clear division of functions. In this paper, the “Triple Helix” theory is used for reference, and the “Triple Helix” theory is introduced into the research framework of China’s advanced nonferrous metal innovation network.

To sum up, the existing research on the evolution of innovation networks has provided a solid foundation and beneficial enlightenment for this study. However, there are few kinds of research on the combination of advanced nonferrous metals and innovation networks. Moreover, in the field of advanced nonferrous metals, scholars mostly start from a static perspective. Comprehensive, systematic, and dynamic research on the patent status and patent cooperation network of the industry needs to be deepened.

Therefore, based on the data of patent cooperation applications of the advanced nonferrous metal industry, this study uses the social network analysis method and Gephi network visualization to analyze the current situation of the nonferrous metal industry in China. The patent cooperation network and knowledge network are constructed from the perspective of the multilayer network, analyzed from the dimensions of the patentee, knowledge element, and geographical distribution, and reveal the structural characteristics and evolution laws of patent cooperation in the advanced nonferrous metal industry from multiple dimensions. It provides a reference for optimizing the patent cooperation network of the advanced nonferrous metal industry, enhancing its technological innovation, and formulating an industrial development strategy.

3. Research Design

3.1. Research Methodology. This paper adopts research methods such as patent bibliometrics, social network analysis, and data visualization. It uses the social network analysis software and its visualization functions such as Gephi and Python to construct the topological structure diagram of patent cooperation and the heat map of patent technology theme evolution in China’s advanced nonferrous metal industry. Also, analyze the network structure index, network structure evolution, and technology topic evolution. The indicators for measuring the patent cooperation network of advanced nonferrous metal industry mainly include the following:

(1) Network size, that is, the number of nodes in the network, reflects the size of the network. The larger the value, the larger the network scale.
(2) The number of network edges, that is, the total number of connections produced by cooperation among network nodes, reflects the network structure relationship. The larger the value, the more complex the network structure.

(3) The average path length is the number of edges in the shortest path between any two nodes \( i \) and \( j \) in the network. \( d_{ij} \) is the distance between nodes, and the average of all the distances between nodes is the average path length of the network, which reflects the average distance between two nodes in the network (Watts and Strogatz collective dynamics of "small world" networks [1]. Nature, 1998, 393 (6684): 440–442). The larger the value, the sparser the network, and the lower the transmission performance and efficiency of the corresponding network. The calculation formula is

\[
PL = \frac{2}{n(n-1)} \sum_{i,j} d(i,j).
\]

(4) The average clustering coefficient, which is a measure of the density of nodes in the network, reflects the average value of the clustering coefficients of all nodes in the network. The larger the value, the easier it is for adjacent nodes to establish cooperative relations. The calculation formula is

\[
C = \frac{1}{n} \sum_{i=1}^{n} \frac{2l_i}{d_i(d_i-1)},
\]

where \( l_i \) refers to the actual number of edges between all nodes connected to node \( i \).

(5) Network density is the ratio of the number of actual relationships in the network to the number of theoretically possible relationships (Liu Jun. An introduction to social network analysis [M]. Beijing: Social Scince Literature Publishing House, 2004: 304–305). The calculation formula is

\[
D = \frac{2l}{n(n-1)},
\]

where the number of nodes is \( n \) and the actual number of edges is \( l \), which reflects the closeness of the network relationship. The larger the value, the closer the network structure and the closer the relationship between network members.

(6) Network diameter is the maximum distance between any two nodes in the network. The larger the value, the sparser the network, and the lower the transmission performance and efficiency of the corresponding network. The calculation formula is

\[
L = \max d(i,j),
\]

where \( i \) and \( j \) represent any two nodes.

3.2. Sample Selection and Data Processing. The patent data used in this research comes from the PatSnap patent database. Download the patent data of the advanced nonferrous metal industry according to the Strategic Emerging Industry Classification and International Patent Classification Reference Relationship Table issued by the State Intellectual Property Office. The specific steps of data search and cleaning are as follows: first, the high-frequency keywords and IPC classification numbers of the advanced nonferrous metals industry are determined according to the classification of the advanced nonferrous metals industry in the document Classification of Strategic Emerging Industries. According to this, the patent search expression of the advanced nonferrous metal industry is determined. The document points out that the technologies covered by the advanced nonferrous metal industry include high-precision copper, pipe, rod, and wire profiles; high-precision copper and tubes, rods, and linear materials; aerospace high-strength aluminum alloy forgings; high-strength and high-conductivity copper materials; electrolytic copper foil, rolled copper foil, electronic copper, medical titanium alloy, metal fiber porous materials, porous titanium and titanium alloy, foam copper, aluminum, nickel, nonferrous metal fiber porous materials, etc. Second, according to the patent search expression, patent data are retrieved through the PatSnap patent database, and 1018491 original patent data are obtained and downloaded. Third, invention patents contain a higher knowledge level of inventors and more value, and are more representative than utility model and appearance patents. Therefore, this study only selects invention applications and authorizes invention patents. The remaining 259579 patents were obtained. Finally, screened patents with more than 2 original patent holders and then continued to exclude patents containing natural-person applicants. A total of 34116 cooperative invention patents in the advanced nonferrous metals industry were obtained as the data basis of this study. Since there is at least an 18-month time lag from patent application to publication, and invention patents tend to take longer from application to publication, the data set in this study is selected up to 2020 as a reference. Because the patent application data for the advanced nonferrous metal industry first appeared in 2002, the scope of this study is from 2002 to 2020.

From Figure 1, it can be seen that the number of joint patent applications for advanced nonferrous metals in China is increasing year by year, and the technological development of an industry will be directly affected by various policies issued by China. This study divides the period of joint patent applications into four development stages, namely: 2002–2007, 2008–2011, 2012–2016, and 2017–2020.

(1) 2002–2007 is the initial period. In 2002, the number of cooperative patent applications in the advanced nonferrous metals industry began to grow from scratch, and it showed a slow development trend until 2007. At this stage, only a few large enterprises cooperated to apply for patents, and the level of patent cooperation was low.
(2) 2008–2011 is a period of rapid growth, and the “12th Five-Year Plan” is a key period for China to build an innovative country. Building a well-off society in an all-round way and accelerating the transformation of the economic development mode put forward higher and more urgent requirements for the construction of innovation capacity. At this stage, the number of cooperative patents increased year by year, with an obvious growth rate.

(3) 2012–2016 is a period of high-quality development. The “13th Five-Year Plan” for the development of the nonferrous metals industry, promulgated by the Ministry of Industry and Information Technology, outlined eight major tasks, including implementing an innovation drive, accelerating industrial restructuring, vigorously developing high-end materials, promoting green sustainable development, improving resource supply capacity, promoting deep integration of the two industries, actively expanding application fields, and deepening international cooperation. The nonferrous metals industry entered a new stage of development after the Fifth Plenary Session of the 18th CPC Central Committee. At this stage, it changed from rapid development to high-quality development, and the number of patents increased as a whole.

(4) 2017–2020 is a period of stable growth or a growth bottleneck period. At this stage, although the number of cooperative patent applications still maintains high-intensity cooperation, the growth rate is slow, far from the rapid development of the previous stage. This may be related to technological bottlenecks and lagging economic development during the epidemic.

According to the above analysis, based on the patent data of the cooperative application, this paper explores the evolution characteristics of the cooperative patent in the advanced nonferrous metal industry from three aspects: the type of original patentee, the region where the original patentee is located, and the technical subject areas involved in the cooperative patent application. The aim is to maintain a stable level of technological innovation for enterprises in the industry during the normalization of the epidemic situation, thus promoting the core competitiveness of enterprises.

4. Analysis of the Evolution Characteristics of Cooperation Networks in the Advanced Nonferrous Metal Industry

4.1. Analysis of the Characteristics of the Overall Industrial Cooperation Network. According to the sample patent data, the patent cooperation network of China’s nonferrous metal industry from 2002 to 2020 was constructed by using Gephi 0.9.2 software, as shown in Figure 2. The cooperative patentees are divided according to the year and imported into Gephi 0.9.2 software in the form of point relationships and edge relationship, respectively. In the diagram, nodes represent types of principals that cooperate with each other. The nodes are divided into four types, which replace enterprises, universities, research institutes, and natural people with different colors. The size of a node represents the number of links between the node and other nodes, that is, the cooperation strength of the node. The connection between nodes represents the cooperative relationship, and the thickness of the connection represents the frequency of cooperation between linked nodes. The thicker the connection, the more frequent the cooperation between nodes in this research period. Generally, the larger the node value, the larger the degree value of the node, and the wider the cooperation range; the thicker the connecting edge, the greater the cooperation frequency between adjacent nodes, that is, the more stable the cooperative relationship between adjacent nodes. As shown in Figure 2, the patent cooperation network of China’s advanced nonferrous metal industry is
disconnected as a whole. Some nodes occupy the core position in the network, forming a larger subnet and several small subnets.

The topological structure indicators of patent cooperation in China’s advanced nonferrous metal industry from 2002 to 2020 are shown in Table 1. It can be seen that many nodes in the network diagram have not yet formed direct connections; the degree of patent cooperation is not sufficient; and the network vitality is insufficient. Most patent applicants have little cooperation and weak connections, and some key applicants act as intermediaries to form a tie to transmit information and connect with other nodes.

Centrality analysis is a key tool to measure the importance of network nodes. This study selects two indexes, degree centrality and betweenness centrality, to explore the important nodes in the patent cooperation network of China’s advanced nonferrous metal industry from 2002 to 2020. The top ten sample invention patent applicants with degree centrality and betweenness centrality are shown in Table 2. Applicants with a strong degree of centrality have a higher position in the network, and they have more subjects to cooperate with, which leads to cooperative relations and makes the network closer. Applicants with a strong betweenness centrality have a strong ability to influence the whole network through cooperation. Some applicants show high status in both centralities, such as State Grid Corp. and Tsinghua University, which rank at the forefront in both centralities; that is, they have higher status in the network and greater influence on the whole network.

4.2. Analysis of Four-Stage Evolution Characteristics of Cooperative Networks. Gephi 0.9.2 software is used to draw the patent cooperation network map of the advanced nonferrous metal industry in four stages: 2002–2007, 2008–2011, 2012–2016, and 2017–2020, as shown in Figures 3–6.

The four evolution analysis charts show the following:

1. Over time, the intensity of cooperation has gradually increased. In the first two stages, there is mainly small-scale cooperation. For example, two or three enterprises cooperate and do not form a complex cooperation network; in the latter two stages, there

Figure 2: The invention patent cooperation network of the advanced nonferrous metals industry in China from 2002 to 2020.
Table 1: Basic attribute index of an invention patent cooperation network of the advanced nonferrous metals industry in China from 2002 to 2020.

| Project Index value | Network size | Number of network edge | Network diameter | Graph density | Average clustering coefficient | Average path length |
|---------------------|--------------|------------------------|------------------|---------------|-------------------------------|---------------------|
|                     | 3010         | 4124                   | 16               | 0.001         | 0.729                         | 5.083               |

Table 2: The degree centrality and betweenness centrality of the whole patent cooperation network of the advanced nonferrous metal industry.

| Applicant                                      | Degree centrality | Applicant                                      | Betweenness centrality |
|------------------------------------------------|-------------------|-----------------------------------------------|------------------------|
| State Grid Corp.                               | 346               | State Grid Corp.                              | 590711.80              |
| China Petrochemical Corporation Limited        | 55                | PetroChina Co., Ltd.                          | 213672.42              |
| Central South University                       | 55                | Tsinghua University                           | 178997.21              |
| Shanghai Jiao Tong University                  | 49                | Shanghai Jiao Tong University                 | 172177.20              |
| Tsinghua University                            | 46                | Central South University                      | 154672.13              |
| University of Science and Technology Beijing   | 39                | China Petrochemical Corporation Limited       | 143446.67              |
| Northeastern University                        | 34                | University of Science and Technology Beijing  | 130471.53              |
| Zhejiang University                            | 32                | Baoshan Iron and Steel Co., Ltd.              | 129023.57              |
| State Grid Smart Grid Research Institute       | 31                | Xi’an Jiaotong University                     | 92493.06               |
| PetroChina Co., Ltd.                           | 30                | Peking University                             | 83922.18               |

Figure 3: An invention patent cooperation network of the advanced nonferrous metals industry in China from 2002 to 2007.
are a large number of small-scale centralized cooperative relationships with certain nodes as the core of cooperation. This shows that enterprises find the limitations of their technology and knowledge in the development process and begin to try to find a more stable cooperative relationship. This relationship can not only help enterprises to open up new technical fields and enhance their technical breadth and depth but also share the uncertainty and risk of technological innovation in the cooperation network. This will greatly reduce the loss of interest that enterprises need to bear due to innovation failure.

(2) The evolution of research subjects is more in line with the trend of integration of industry-university-research. Colleges and universities have more patent knowledge and rich theoretical resources, but there is no way to transform patented technology well without product demand and financial strength. Enterprises have the economic strength to bring patented technology to the ground, but a lack of knowledge support from patent developers leads to the lack of patented technology. The full combination of industry-university-research is helpful to realize the collaborative transformation process from patent knowledge to product profit. We can see from Figures 3 to 6 that in the initial stage, there is more cooperation between natural persons and enterprises. However, over time, more and more cooperative relations have been formed, with universities as the "stamens" and various types of enterprises as the "petals." This relationship can promote the flow and transformation of knowledge and technology, thus enhancing the success of invention patents in enterprises and the efficiency of patent transformation in colleges and universities.

To further analyze the structural changes of the patent cooperation network of advanced nonferrous metals, the structure index of the advanced nonferrous metal patent cooperation network is measured by using the social network analysis method. The change in topological structure characteristics is shown in Table 3.
The network nodes reflect the network scale. As can be seen from Table 3, the scale of the patent cooperation network in China’s advanced nonferrous metal industry is building up. The network scale values show that the value of network nodes in stage 1 is 275, that in stage 2 is 1025, that in stage 3 is 2088, and that in stage 4 is 2567. From stage 1 to stage 4, the number of network edges has the same trend as that of network nodes, but the change speed of network edge number is more elastic than that of network scale. This can be reflected by graph density, which decreases gradually with the change of stages, which shows that the cooperation relationship and cooperation times between network nodes are increasing.

The average clustering coefficient reflects the close relationship between the whole network. The clustering coefficients of the four stages are much higher than the network density of the same stage, which shows that the establishment of an invention patent cooperation relationship in China’s advanced nonferrous metal industry is not a random choice. There is preferred connectivity, and a stable cooperative relationship is gradually formed. The network diameter and average path length are also rising, which shows that the cooperation network of the Chinese advanced nonferrous metal industry is becoming more and more sparse. The increase of network nodes in the network makes the distance between nodes far away, which leads to the decline of network transmission performance and efficiency of network nodes. This shows that although there are more and more subjects participating in cooperation in this field in China, there is still a large cooperation space among innovative subjects. Generally speaking, the four stages of the evolution of the network have the characteristics of a high clustering coefficient and a small average path distance, showing a distinct small-world effect. This is conducive to the sharing of resources and information in the network and facilitates the exchange and cooperation between applicants.

4.3. Evolution Analysis of Important Nodes. From the analysis of cooperative networks, it can be seen that the networks in each stage are comparable. Select two indexes, degree centrality and betweenness centrality, to analyze the
top ten nodes of the two indexes in each stage. It can reflect the importance of reflecting nodes and analyze the changing characteristics of important nodes in each stage.

As shown in Table 4, from the point of view of degree centrality, the most active applicants are enterprises, universities, and scientific research institutions, which form a relatively stable cooperation mode of “industry-university-research.” From the point of view of centrality value, from the initial company as the main core to the later university as the core, the weight of universities is getting bigger and bigger. From 2002 to 2007, there was more patent cooperation related to the petrochemical industry, which made Sinopec and its research institutes rank 1 and 2, respectively, and the proportion of enterprises, universities, and scientific research institutions was equal; from 2008 to 2011, the composition structure of patent applicants is similar to that of the first stage, and enterprises still occupy an important position. However, it can be seen that Zhejiang University and Tsinghua University have gradually become the subcore nodes of the network, indicating that universities have

Figure 6: An invention patent cooperation network of the advanced nonferrous metals industry in China from 2017 to 2020.

Table 3: Structural characteristic values of invention patent cooperation networks in different stages of China’s advanced nonferrous metal industry.

| Index                  | Stage 1: 2002–2007 | Stage 2: 2008–2011 | Stage 3: 2012–2016 | Stage 4: 2017–2020 |
|------------------------|---------------------|---------------------|---------------------|---------------------|
| Network size           | 275                 | 1025                | 2088                | 2567                |
| Number of network edge | 254                 | 988                 | 2338                | 3404                |
| Network diameter       | 6                   | 11                  | 14                  | 16                  |
| Graph density          | 0.006               | 0.002               | 0.001               | 0.001               |
| Average clustering coefficient | 0.738            | 0.721               | 0.713               | 0.732               |
| Average path length    | 2.77                | 5.03                | 4.99                | 5.29                |
Table 4: The degree centrality and betweenness centrality of the patent cooperation network in each stage of advanced nonferrous metal industry.

| Time          | Applicant                                                                 | Degree centrality | Applicant                                      | Betweenness centrality |
|---------------|---------------------------------------------------------------------------|-------------------|------------------------------------------------|------------------------|
| 2002–2007     | China Petrochemical Corporation Limited                                   | 30                | China Petrochemical Corporation Limited        | 665.67                 |
|               | Sinopec Company Petrochemical Science Research Institute                 | 9                 | Zhejiang University                            | 494                    |
|               | Baoshan Iron and Steel Co., Ltd                                          | 9                 | Baoshan Iron and Steel Co., Ltd                | 368                    |
|               | Consortium corporation Industrial Technology Research Institute           | 7                 | China Petrochemical Corporation Limited        | 205.67                 |
|               | Zhejiang University                                                      | 7                 | East China University of Science and Technology| 132                    |
|               | Wanguo Computer Co., Ltd                                                 | 6                 | Sinopec Ningbo engineering Co., Ltd            | 117.33                 |
|               | East China University of Science and Technology                          | 5                 | Petrochemical Science Research Institute of    | 110.67                 |
|               |                                                                           |                   | China Stone Engineering Company               |                        |
|               | Tsinghua University                                                      | 5                 | Dalian Institute of Chemical Physics, Chinese  | 89                     |
|               |                                                                           |                   | Academy of Sciences                            |                        |
|               | China University of Petroleum (Beijing)                                   | 5                 | Antai Technology Co., Ltd                      | 45                     |
|               | Xiwang Technology Co., Ltd                                               | 5                 | University of Chongqing                        | 45                     |
| 2008–2011     | China Petrochemical Corporation Limited                                   | 23                | China National Petroleum Corporation Limited   | 2230.5                 |
|               | Baoshan Iron and Steel Co., Ltd                                          | 12                | China Petrochemical Corporation Limited        | 2192.36                |
|               | Zhejiang University                                                      | 11                | Dalian Institute of Chemical Physics, Chinese  | 2090.33                |
|               | Tsinghua University                                                      | 10                | Academy of Sciences                            | 1483.5                 |
|               | Dalian Institute of Chemical Physics, Chinese Academy of Sciences        | 10                | Baoshan Iron and Steel Co., Ltd                | 1464.67                |
|               | University of Science and Technology Beijing                             | 9                 | University of Science and Technology Beijing   | 1225.67                |
|               | Hon Hai Precision Industries Company Limited                             | 7                 | Zhejiang University                            | 1208.6                 |
|               | China National Petroleum Corporation Limited                             | 6                 | Shanghai Jiao Tong University                  | 756.64                 |
|               | Shanghai Jiao Tong University                                            | 6                 | Shandong Aluminum Co., Ltd                     | 557                    |
|               | East China University of Science and Technology                          | 6                 | University of Science and Technology Beijing   | 2843.51                |
|               |                                                                           |                   | Central South University                       | 2026.67                |
| 2012–2016     | Tsinghua University                                                      | 22                | China National Petroleum Corporation Limited   | 5530.62                |
|               | China Petrochemical Corporation Limited                                   | 17                | Tsinghua University                            | 4273.33                |
|               | Shanghai Jiao Tong University                                            | 16                | Baoshan Iron and Steel Co., Ltd                | 3769.08                |
|               | Central South University                                                 | 15                | University of Science and Technology Beijing   | 3277.58                |
|               | Zhejiang University                                                      | 13                | China Petrochemical Corporation Limited        | 3113.59                |
|               | Dalian Institute of Chemical Physics, Chinese Academy of Sciences        | 12                | Dalian University of Technology                | 2950.09                |
|               | Hon Hai Precision Industries Company Limited                             | 11                | Shanghai Jiao Tong University                  | 2843.51                |
|               | University of Science and Technology Beijing                             | 11                | Central South University                       | 2026.67                |
|               | China Petrochemical Corporation Limited                                   | 10                | Dalian Institute of Chemical Physics, Chinese  | 1583                   |
|               |                                                                           |                   | Academy of Sciences                            | 1350.1                 |
|               | Baoshan Iron and Steel Co., Ltd                                          | 9                 | Zhejiang University                            | 1350.1                 |
| 2017–2020     | Shanghai Jiao Tong University                                            | 23                | University of Science and Technology Beijing   | 3945                   |
|               | Tsinghua University                                                      | 18                | Central South University                       | 3824                   |
|               | Central South University                                                 | 18                | Baoshan Iron and Steel Co., Ltd                | 3548                   |
|               | University of Science and Technology Beijing                             | 15                | Tsinghua University                            | 2465                   |
|               | China Petrochemical Corporation Limited                                   | 14                | Shanghai Jiao Tong University                  | 2269                   |
|               |                                                                           |                   | Central South University                       |                        |
|               | Hon Hai Precision Industries Company Limited                             | 12                | CRRC Industrial Research Institute Co., Ltd    | 2088                   |
|               | Zhejiang University                                                      | 11                | China Petrochemical Corporation Limited        | 1039.5                 |
|               | Shanghai University                                                      | 11                | Hon Hai Precision Industries Company Limited   | 954                    |
|               | China University of Petroleum (East China)                                | 9                 | Dalian University of Technology                | 946                    |
|               |                                                                           |                   | Beijing Steel Research and Advanced Technology|                        |
|               | Baoshan Iron and Steel Co., Ltd                                          | 9                 | co., Ltd                                         | 824.33                 |
strong technological innovation capabilities and rich patent cooperation relations; from 2012 to 2016, different from the previous two stages, there are 5 universities, accounting for half of the applicants, and Tsinghua University is the main core node of the network. The strong technological innovation and strong patent cooperation application intention of universities appear; from 2017 to 2020, like the third stage, universities are still the main ones, with 7 university applicants, most of whom are at the forefront, and the status of universities has increased.

According to each stage of betweenness centrality, it can be seen that the composition structure of applicants is still dominated by enterprises, universities, and research institutes, and the value of betweenness centrality gradually increases in different stages. The influence of the third and fourth stages is more obvious, and the control power of the network is stronger. From 2002 to 2007, enterprise applicants accounted for half, which had strong control over the network, followed by universities, which showed relatively weak influence; from 2008 to 2011, similar to the previous
stage, the applicants with more patent cooperation are still enterprises, and most of them are concentrated in companies in the fields of petroleum, chemical industry, and natural gas. Also, the betweenness centrality value increases, which shows that it has stronger control power than the first stage in the network; from 2012 to 2016, there are a large number of college applicants, occupying strong network control, but enterprises still have the strongest leading patent cooperation ability; from 2017 to 2020, the number of applicants from colleges and universities has increased in both the number and the intensity of control, which can effectively influence patent cooperation.

It can be seen that the ranking structure of the betweenness centrality and the degree centrality of the network is different, and the universities have increased the ranking of the two types of centralities. It reflects that colleges and universities are playing an increasingly important role in the network and have gradually acquired strong control power, which can effectively influence patent cooperation. Some applicants have a position before the exam in both types of
centralities, such as China Petrochemical Corporation, Tsinghua University, and China National Petroleum Corporation. It shows that these members play an important intermediary role in contacting other members, building a "bridge" for cooperation among other members, and grasping the general direction of technical cooperation.

5. Analysis of the Evolution Characteristics of Knowledge Networks in the Advanced Nonferrous Metal Industry

5.1. Evolution Characteristics of Cooperative Patent Application Technology Field. In order to have a deeper understanding of the fields involved in patented technology and the R & D intensity invested in each field in the advanced nonferrous metal industry, Python is used to draw the thermal map of patented technology theme evolution and Gephi0.9.2 is used to draw the patented technology co-occurrence map. We can visually analyze the depth and co-occurrence of technology. Figures 7–10 represent technology-intensive fields, technology-tentative areas, and technology-developmental areas, respectively. In the figures, the horizontal axis represents the fields where patented technologies are distributed; the vertical axis represents the passage of years; and the color progressive bars on the right represent the number of patented technologies from less to more. In the heat map, we can see the development process of technical fields vertically, and we can see the development and changes of various technical fields with the change of years horizontally.

From Figure 7, we can see that the technology-intensive distribution areas of the advanced nonferrous metal industry are B01, B21, B22, B23, C01, C07, C09, C22, C23, and H01. The overall total amount is more than 800. The top three in total are B01 (general physical or chemical methods or devices), H01 (basic electrical components), and C01 (inorganic chemistry), with 7001 times, 6444 times, and 5176 times, respectively. It can be seen from the figure that the evolution of various technical fields shows a trend from shallow to deep, and these technical fields are the main research fields of the advanced nonferrous metal industry.

Figures 8 and 9 show the evolution characteristics of technical topics in different fields at the frequency of 0–10. From the ordinate point of view, this part of the field spans a wider range, with a total of 72 categories, but the total number is only 840 times, which belongs to a wide range but a small number of tentative technical fields. This field is divided into two types of technologies with different characteristics. One is research that advances with time and keeps continuity, and the research intensity increases year by year, such as C30 (crystal growth), E21 (drilling of soil or
rock; mining), G06 (calculation; reckoning or counting), etc. The patented technologies in these fields are likely to grow into patented technologies in developmental fields and auxiliary intensive technology fields through continuous cooperation and development; the other is that it occasionally appears in the progress of time, forming intermittent research. Also, the total amount is very small, for example, C05 (fertilizer; fertilizer manufacturing), C06 (dynamite; matches), A23 (food or food products not included in other categories; and their handling), etc. The actual effect of patented technology inventions in these fields is not great, or it is difficult to research and develop, and the benefits are small, so this kind of technology does not have good research value.

Figure 10 shows the technical fields in the frequency range of 0–80, and the number is about one-tenth of the technology-intensive fields, which play an auxiliary role in patents in the intensive fields. The number is about 8 times that of the tentative field, which belongs to the field with higher research value and significance. Similar to the tentative field, there are two types of technologies in this field. One is a technology that may become an intensive technology field in the future, such as C25 (electrolytic or electrophoretic processes; equipment used). This kind of technology shows the phenomenon of continuous research with time. The research intensity is more than that of previous years, and it also invests more in research than other technologies. There is a great research gap, but it should have its own research value and significance. Enterprises, universities, and research institutes can increase research on this part of technology. The other is an experimental development technique that shows signs of disappearing as it matures over time, with a few studies appearing early on, such as H04 (electrical communication technology). Or there is the phenomenon of staged technology research and development, such as B32 (layered products). This kind of technology does not have strategic support for the innovation and development of enterprises. Therefore, enterprise should reduce their research and development investment in this kind of technology.

From the above analysis, we can see that technological innovation institutions should keep continuous research in intensive technology fields to lay the foundation of innovation competitiveness. Enterprises that master the core competitive advantages of the industry can have good basic development abilities in the advanced nonferrous metal industry. In addition, the innovation subject can also separate some innovation resources, cooperate with enterprises, universities, and research institutes with heterogeneous resources, and then seek the blue ocean field of technology in the field of technology development and tentative fields. Good development research in this field can provide stable
technical assistance advantages for enterprises and even occupy the leading resources in the future development of technical fields, providing a high-quality guarantee for their innovation competitiveness.

5.2. Analysis of Four-Stage Evolution Characteristics of Knowledge Networks. Through the analysis of the above-mentioned patent categories, we can see which categories the advanced nonferrous metal industry should conduct in-depth research. Within each category, the success and availability of patent research and development can be enhanced by studying the cooperative research and development of patent subcategories. This paper is based on the subclass data of the IPC classification number of a cooperative patent application. The Gephi 0.9.2 is used to construct the IPC co-occurrence network diagram of patented technology to analyze the characteristics and evolution law of the knowledge network. Figures 11–14 show the co-occurrence evolution process of IPC classification numbers in four stages, and Table 5 shows the co-occurrence topological index of cooperative patented technologies in the advanced nonferrous metal industry. The node in the network represents a subclass of the IPC classification number, and the larger the node, the more times the IPC appears; the connection represents a co-occurrence of two classification numbers, and the thicker the connection, the more co-occurrence frequency of nodes at both ends of the connection, which shows that the two technologies are more closely related.

With the evolution process diagram and the co-occurrence topological indicators shown in Table 5, it can be analyzed as follows:

(1) The network scale is increasing gradually, from 112 nodes at the beginning to 325 nodes, which shows that the cooperative patents of the advanced nonferrous metals industry contain more and more knowledge elements. It can also be seen from the growth of network connections and the average degree that the frequency of co-occurrence between technologies has also increased by a greater margin. It shows that the intensity of technological co-occurrence is getting bigger and bigger, and patents gather more and more technical cooperation. This requires enterprises to seek more partners with heterogeneous resources for patent technology cooperation.

(2) From the network diameter and graph density, we can see that the technology co-occurrence network is getting closer and closer. With the increasing number and complexity of network scale and network connections, the network diameter decreases step by step, and the graph density increases and stabilizes gradually, which shows that the
technology is characterized by overall dispersion and local tightness. More research on IPC technology subcategories included in intensive technology fields is conducive to the promotion of core competitiveness.

(3) From the average clustering coefficient and average path length, it can be seen that the four stages have the characteristics of a high average clustering coefficient, low average path length, strong network cohesion, and small-world effect. There are relatively close technologies. R & D institutions should identify these technologies and cooperate in research, and cooperate to develop more comprehensive patents, thereby enhancing their innovation ability and core competitiveness.

6. Conclusion

Taking the advanced nonferrous metal industry as an example, this study constructs the invention patent cooperation network, the heat map of patent technology theme evolution, and the patent technology IPC co-occurrence network of the advanced nonferrous metal industry in China from the perspective of cooperation network and knowledge network from 2002 to 2020. Furthermore, we deeply study the structural characteristics and evolution law of the
invention patent network in the advanced nonferrous metal industry and draw the following conclusions and give relevant suggestions.

6.1. Crucial Findings.

(1) The scale of patent cooperation networks in China’s advanced nonferrous metal industry is expanding day by day. The network density is increasing, the network cohesion is strong, and the small-world effect is obvious. It shows the characteristics of overall dispersion and local tightness, and there are few “bridges” between groups, so the network still has great room for development. The “Triple Helix” feature of the cooperation network is gradually obvious. In the long-term formal and informal cooperation and exchanges, universities, enterprises, and scientific research institutes have crossed, closely cooperated, and interacted with each other, and the cooperative relationship has become more stable. The evolution of knowledge networks over time shows the characteristics of technological dynamic changes.

(2) Patent applicants such as China Petrochemical Corporation, Tsinghua University, China National Petroleum Corporation, Zhejiang University, Baoshan Iron and Steel Co., Ltd., and Shanghai Jiaotong University are important nodes of the network. These nodes have more contact with other nodes, play an intermediary role, are the “bridge” for cooperation among other subjects, and grasp the general direction of technical cooperation. Therefore, these core nodes should be the key breakthrough points to guide and adjust the cooperation behavior of important nodes; with time, the structure of key nodes that play a leading role has changed from the initial enterprise-led to university-led.

(3) The total number of technology categories involved in the advanced nonferrous metal industry is increasing, and the depth is also gradually increasing. Different types of technology fields are presented, including technology-intensive fields, tentative technology fields, and technology development fields, which are characterized by high intensity, wide range, and steady progress.

6.2. Policy Implications. To speed up the cultivation of China’s advanced nonferrous metal industry, realize the optimal allocation of innovative resources, and improve international competitiveness, this paper puts forward the following theoretical and practical enlightenment.

(1) The government should strengthen and guide the cooperative relationship of the “Triple Helix” subjects to promote the stability and development of the innovation network among industries, universities, and research. The government should introduce relevant policies to promote the breakthrough of the core technology of China’s advanced nonferrous metal industry, guided by industrial demand and aimed at tackling key problems with new technologies. Encourage innovative organizations to focus on the core common technologies of the industry to carry out joint research and achieve breakthroughs in the core technologies of the industry with the strong support of the government’s science and technology support plan.

First of all, the government should set up an incentive mechanism to actively guide research institutions such as universities and research institutes to realize the transformation of patented technology through cooperation with enterprises. Second, the government should establish a dynamic management and evaluation system for industry-university-research cooperation projects, constantly adjust the deployment of industry-university-research cooperation projects, and strengthen the tracking and implementation of policies. Finally, the government should improve the intellectual property system and build a long-term protection mechanism for intellectual property rights.

(2) In the stage of knowledge innovation, universities have created a large number of scientific research achievements through collaborative innovation with governments, enterprises, and research institutions. However, most of them exist in the form of papers or patents and do not transform knowledge into capital, which leads to the waste of technological innovation. Therefore, universities should give full play to their advantages in the process of knowledge innovation and extend this advantage to the field of technological innovation to realize the capitalization of knowledge.

In addition, universities and research institutions should focus on the core common technologies of industrial development to fundamentally solve the “two skins” problem of the current science and technology economy. Because they have overlapping functions in scientific research and personnel training, they can break the original organizational boundaries and develop synergistically through the deep integration of scientific and technological resources by integrating resources such as science, technology, and talents with universities and scientific research institutions to promote the deep integration of basic research and applied research personnel training, which can realize the superposition of high-quality resources and complementary advantages, thus driving the sustainable development of regional economies and societies.

(3) Strengthen the dominant position of enterprises in technological innovation; support enterprises to enhance their independent innovation ability; and establish and improve the enterprise-led collaborative innovation mechanism of industries, universities and research. Enterprises, as the main battlefield and the
realizing party of scientific and technological achievements, can accelerate the process of knowledge capitalization and technology industrialization through collaborative innovation. However, most Chinese enterprises pay insufficient attention to basic research, which leads to the weak dominant position of enterprises in the innovation network, and their lack of scientific and technological innovation ability leads to loose cooperative relations, which has become an important factor restricting the development of China’s “Triple Helix” collaborative innovation system.

Enterprises can enhance their innovation abilities, at the same time, they can carry out technical cooperation with other enterprises to promote the formation and implementation of patent alliances to enhance their innovation advantages. On the other hand, it can cooperate with university research institutions to realize the transformation and docking of resources and provide strong support for technological innovation and achievement transformation.

(4) In practice, the government should guide advanced nonferrous metal enterprises to increase investment in basic research of core technologies in the industry through leveraged means such as financial subsidies and interest subsidies. Encourage enterprises to improve their scientific research ability by building laboratories or R & D centers jointly with university research institutes.

Based on macropolicy support, the government can also build innovation carriers to participate in collaborative innovation. For example, the establishment of new industry research institutes and technology incubators. The new industry research institute is an innovative platform for deep integration of industry, education, and research, which is jointly sponsored by key universities and research institutions of key enterprises in the industry under the guidance of the government to carry out collaborative innovation and core technology breakthroughs and tackle key problems. The new industry research institute pays attention to the interconnection of basic research and applied research to realize the effective connection of “basic research-technological tackling-technical application-successful industrialization.” The technology incubator is one of the carriers of science and technology innovation services and the training base of innovative and entrepreneurial talents. Among them, the government provides infrastructure such as sites, as well as preferential policies, such as seed funds and taxes. A technology incubator helps to improve the conversion rate of scientific and technological achievements and reduce the risks and costs of start-up enterprises. Through these methods, it is beneficial to solve the dilemma of obstacles in knowledge transfer across organizations caused by the mismatch of knowledge and ability between advanced nonferrous metal enterprises and universities and research institutes in China, and fundamentally solve the phenomenon of “two skins” between science and technology and the economy.

Data Availability
The data used for this study are available upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest.

Authors’ Contributions
All the authors contributed equally to this work.

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