III. Chemical, Metallurgical & Materials Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the disciplines of chemical, metallurgical, and materials engineering assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 1.1.1. Table 1.1.2 shows the numbers of their core papers that have been published in recent years. Among these 10 research hotspots, the research kernel for "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors," "Application of composite adsorbents for wastewater treatment," "Preparation and applications of functional gradient materials," "Preparation of porous surfaces and their applications in enhanced heat transfer," "Construction and application of superhydrophobic surfaces," and "Hydrogen storage alloy materials" is to obtain suitable materials for novel applications. The hotspots of "*In situ* transmission electron microscopy" and "Hydrogen sulfide sensors" mainly involve analytical and detection studies while "Carbon-hydrogen bond activation" greatly relates to synthetic chemistry. The total number of papers that have been published from 2011 to 2016 relating to each hotspots among the top 10 is about 50. For the topics of "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" and "Hydrogen sulfide sensors," the average citation for each paper exceeds 100. The average publication year for the core papers "Application of composite adsorbents for wastewater treatment," "Preparation and applications of functional gradient materials," and "Carbon-hydrogen bond activation" is 2014. The proportion of consistently cited papers of "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" and "Application of composite adsorbents for wastewater treatment" exceeds 50%. As shown in Table 1.1.2, the published papers that relate to "*In situ* transmission electron microscopy,"

Table 1.1.1 Top 10 engineering research hotspots in chemical, metallurgical, and materials engineering

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors	48	7395	154.06	2012.96	66.70%	0
2	Gas separation membranes	49	2154	43.96	2013.51	12.20%	1
3	Application of composite adsorbents for wastewater treatment	48	1756	36.58	2014.04	52.10%	0
4	*In situ* transmission electron microscopy	49	2419	49.37	2013.69	8.20%	2
5	Preparation and applications of functional gradient materials	47	2091	44.49	2014.77	44.70%	1
6	Preparation of porous surfaces and their applications in enhanced heat transfer	50	4095	81.90	2013.06	28.00%	2
7	Carbon-hydrogen bond activation	48	2349	48.94	2014.48	35.40%	0
8	Construction and application of superhydrophobic surfaces	48	2409	50.19	2013.27	10.40%	2
9	Hydrogen sulfide sensors	49	5262	107.39	2012.59	40.80%	0
10	Hydrogen storage alloy materials	49	1249	25.49	2013.76	6.10%	0

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in chemical, metallurgical, and materials engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors	7	6	20	12	3	0
2	Gas separation membranes	6	8	7	14	11	3
3	Application of composite adsorbents for wastewater treatment	3	2	10	13	15	5
4	*In situ* transmission electron microscopy	3	9	6	15	14	2
5	Preparation and applications of functional gradient materials	1	1	4	7	23	11
6	Preparation of porous surfaces and their applications in enhanced heat transfer	8	9	16	7	9	1
7	Carbon-hydrogen bond activation	0	0	7	16	20	5
8	Construction and application of superhydrophobic surfaces	6	8	16	5	11	2
9	Hydrogen sulfide sensors	8	17	15	6	2	1
10	Hydrogen storage alloy materials	8	3	7	12	13	6

"Hydrogen sulfide sensors," "Preparation and applications of functional gradient materials," "Carbon-hydrogen bond activation," and "Hydrogen storage alloy materials" are all continuously increasing. Some experts regard "*In situ* transmission electron microscopy," "Hydrogen sulfide sensors," and "Hydrogen storage alloy materials" as the relatively new and emerging research hotspots, while others consider them to be further advancements of traditional studies. Some research, such as the development of rapid and highly sensitive detection technology in "Application of composite adsorbents for wastewater treatment," *in situ* observation and reaction control at the atomic scale in "*In situ* transmission electron microscopy," and direct conversion into high value functional chiral molecules from simple and non-functionalized substrates in "Carbon-hydrogen bond activation," may result in the emergence of revolutionary technologies.

(1) Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors

$NiCo_2O_4$ is a complex transition metal oxide, which possesses a typical spinel structure. As $NiCo_2O_4$ can store energy via a redox reaction that takes place on its surface and inner body, it has been widely used in electrocatalysis and energy storage. Meanwhile, it also attracted significant attention as an electrode material for supercapacitors owing to its excellent electrical conductivity, catalytic activity, and exceptive magnetic behavior. Although $NiCo_2O_4$ has large specific surface area, the poor electron and ion transportation weakens its cycling stability, which is a crucial problem that needs to be solved. One possible solution to overcome this limitation is to incorporate $NiCo_2O_4$ into various nanostructures such as nanorods, nanosheets, nanorings, hierarchical porous nanoflowers, and hollow nanospheres. As these nanostructures effectively cover the entire surface area of the electrode and facilitate the transport of ions, the activation performance and high ratio properties of this material can be improved. The latest trend in this area involves fabrication of thin-film and nanoarray electrode materials for use as supercapacitors. Direct deposition on the substrate makes it possible to avoid the detrimental effects arising from the use of adhesives, and results in a lower contact electrical resistance and higher surface utilization. Meanwhile, electrode films with nanoarray structures exhibit stronger ability to resist volume change, thus improving the stability and cycle life of the materials.

(2) Gas separation membranes

Gas separation membrane technology, owing to its highly efficient, energy-saving, and green attributes, is a prospective field of study in chemical separation applications. The permeation coefficients of conventional membranes are often low and unable to meet the requirements of large-scale applications. Thus, the development of membrane materials with both high permeability and high selectivity is an important research direction. Polymers with intrinsic microporosity (PIMs) are a novel organic microporous materials that have been attracting increasing attention in recent years. The microporous structure is generated as a result of the ineffective folding of rigid, twisted molecular chains. Accordingly, PIMs are endowed with some distinct advantages such as high specific surface area, high physicochemical stabilities, and a controllable microporous structure. The design and utilization of novel, high-performance PIM membranes is expected to have a great and far-reaching impact on the sustainable development of gas separation membranes.

(3) Application of composite adsorbents for wastewater treatment

Modern industries and occasional emergencies such as a nuclear power plant leak accident are primarily responsible for environmental pollution. Pollution of natural resources is also serious, especially that of water bodies by phosphates, heavy metals, and radioactive elements. Thus, it is vitally important to investigate the visual detection of metal elements in polluted water and remove them in an efficient manner. The visual detection is based on the color change of the detectors when they come into contact with polluting elements. This method allows for the rapid and sensitive observation and identification of contaminants with the naked eye, and therefore, this technique has been attracting significant attention from the scientists. In order to efficiently absorb and remove the contaminating metal elements, it is necessary to investigate and develop novel effective composite and conjugate adsorbents. These adsorbents should be easy to regenerate and reuse, and not cause secondary environmental pollution. In particular, there is tremendous demand for the development of high-performance adsorbents for the removal of toxic elements at trace concentration levels in drinking water, as well as in presence of interfering ions in wastewater. These demands for composite and conjugate adsorbents for water treatment and visual detection of contaminants have become a hotspot in recent research.

(4) *In situ* transmission electron microscopy

In situ transmission electron microscopy (TEM) is used for real-time observation and recording of the dynamic response of the samples placed within the electron microscope to different external excitation signals. *In situ* TEM is one of the most promising techniques for the characterization of structures of materials. It has several advantages such as high spatial and energy resolution of conventional transmission electron microscopy in combination with the real-time, *in situ* observation of the dynamic microstructure of the material, and both quantitative and qualitative assessment of the response behavior to the external incentive of the material. *In situ* TEM has been applied in materials science, catalysis, and life science, and for the study of energy storage materials. Furthermore, it is possible to study reaction mechanisms by real-time observation and control gas phase and liquid phase reactions at the atomic scale by using this technique.

(5) Preparation and applications of functional gradient materials

Functional gradient materials (FGMs) lack distinct interfaces and are novel mixtures that are characterized by their gradually varying composition, density, and structure over their volume, resulting in corresponding gradual changes in their properties. The research efforts in the field of FGMs primarily include material design, preparation, and property assessment. In particular, the property assessment of the FGMs is critical in their investigation. As FGMs are distinct from the traditional homogeneous materials, the conventional test methods are not compatible with this new type of material. Currently, there is no unified standard for the assessment of FGMs, and the investigations merely focus on the heat insulation, thermal fatigue, and thermal shock, in addition to fundamental thermal and mechanical properties. The assessment of FGMs is a subject that relates to thermodynamics, theory of heat transfer, mechanics of materials, and materials engineering, among other issues. Therefore, an accurate, reasonable, and systematic standard assessment method is essential. It is also expected that further research in physics and chemistry will result in an explosion of the practical applications of FGMs.

(6) Preparation of porous surfaces and their applications in enhanced heat transfer

Porous surfaces typically exhibit good heat transfer performance, and they can be prepared following two different manufacturing methods: Either the surface is covered with a porous structure or the structure is perforated and converted into a porous surface. Specifically, the surface can be covered with a layer of porous copper, aluminum, stainless steel, and other alloys by either sintering the metal powder, or electroplating, flame-spraying, and covering the metal screen. On the other hand, a porous surface with holes used as a heat transfer surface can be also prepared by mechanical processing, electrochemical corrosion, and laser processing. The key to preparation of high-quality porous surfaces is the precise control of pore size, uniform distribution, and porosity. A high porosity may adversely affect the strength of the material. It is also necessary to consider the long-term repeatability and reliability of the porous surface in practical applications. The material parameters of the porous surface, the dimensional parameters of the porous structure, and the boiling agent, all have a great influence on the liquid flow and heat transfer during the boiling process. The existing assumptions and theoretical models are not yet perfect, and further research on the boiling heat transfer mechanism and mathematical models of porous surfaces needs to be carried out. In addition, an important part of future research involves a combination of porous surfaces and other enhanced heat transfer measures to bolster the boiling heat transfer technology.

(7) Carbon-hydrogen bond activation

C—H activation is the process of selectively breaking a C—H bond at a specific location in the presence of a metal catalyst and converting it into either a C—X bond or a C—C bond. Many functional organic molecules can be constructed via C—H bond activation with better atom economy. As a result, this transformation has attracted intensive attention from both academia and industry, and has become one of the most important research focuses in the field of organic chemistry in recent years. However, the C—H activation reaction usually requires the presence of a directing group in the organic molecule, which greatly limits the possible structures that can produced. In recent years, the introduction of removable bidentate auxiliary group such as 1-(pyridin-2-yl)propan-2-amine and 8-aminoquinoline as directing groups has successfully expanded the scope of the C—H activation reactions. C—H activation is usually catalyzed by noble metal complexes, such as palladium and rhodium complexes. Recent studies have shown that some cheap transition metal compounds, such as nickel, copper, and even iron can effectively catalyze C—H activation reactions. The synthesis of chiral compounds via asymmetric C—H activation has also achieved a breakthrough by using a chiral ligand as the directing group. This method allows simple and non-functionalized substrates to be directly converted into functional chiral molecules with high value, representing a very attractive modern synthetic strategy. The activation of C—H bonds typically proceeds via a metal containing heterocyclic intermediate, and the subsequent oxidation of the metal center toward C—H bonds is often the rate determining step. Although significant progress has been made, the mechanism for metal ion-mediated catalytic C—H activation needs further investigation, and the efficiency of the catalysts also needs to be significantly improved. It is expected that in the future, the C—H activation reaction will be widely applied in chemical synthesis as new chelating auxiliary groups are being continually discovered and the catalyst efficiency has greatly enhanced in recent years.

(8) Construction and application of superhydrophobic surfaces

Generally, surfaces with a water contact angle larger than 150° are regarded as superhydrophobic (SH) surfaces. There are two typical SH surfaces: the lotus effect and the petal effect states, which are based on the magnitude of the water adhesive force. The SH surfaces possess a great potential in a variety of applications such as oil/water separation, self-cleaning, antifogging, anti-corrosion, drag reduction, microfluidic systems, and liquid transportation. Generally, the wettability of solid surfaces is governed by their surface free energy and surface geometry. A common approach toward imparting superhydrophobicity to a surface involves roughing a hydrophobic surface by constructing hierarchical structures and decreasing its surface energy by modifying with low-surface energy materials. Although significant advances have been made to the theory and applications of the SH surfaces, surface wettability is a complex scientific problem which involves considering many surface parameters together. In particular, some new emerging surface phenomena bring new challenges to the traditional theories and concepts. Therefore, significantly more experimental investigations are needed for practical applications of SH surfaces. Presently, their practical applications are limited by the complicated synthesis techniques, requirement of special equipment, environment polluting technologies, high costs, small size, and poor mechanical properties. A simple, low-cost, environment-friendly, and large-scale method for the construction of artificial SH surfaces is crucial and highly desirable for their adoption and use on an industrial scale. In addition, the mechanical durability of superhydrophobic surfaces remains a great challenge today for their practical applications. Therefore, further fundamental investigations are still necessary to develop wear-resistant, anti-ageing, and large-scale SH surfaces, and such advances are expected to have a significant effect on expanding the applications and improving the performance of SH materials.

(9) Hydrogen sulfide sensors

Hydrogen sulfide sensors are utilized for the rapid detection and analysis of hydrogen sulfide (H_2S) concentration in a specific situation. Several fields such as biology, chemical industry, and environment require the determination of hydrogen sulfide concentration, particularly trace amounts. The traditional methods employed for the determination of trace H_2S include the use of infrared, electrochemical, catalytic, and semiconductor sensors. Although H_2S sensors have different requirements depending on the occasion, they generally require high precision, high sensitivity, a large linear range, strong anti-interference ability, high stability, and a reliable and reproducible performance. The current research focuses mainly on two types of sensing devices, namely, fluorescence and electrochemical sensors. The key to sensing technology is to find or synthesize materials that can selectively respond to H_2S and use them to determine its concentration. This can be achieved by evaluating the intensity change of some physical properties (such as spectral or electrochemical properties) when the sensor comes into contact with different concentrations of H_2S. In different situations, other substances coexisting with H_2S may become interfere with the sensing response. Therefore, different types of sensors need to be developed and used for different occasions in order to achieve rapid and accurate detection of hydrogen sulfide.

(10) Hydrogen storage alloy materials

Hydrogen storage materials can effectively solve the problem of hydrogen storage and transport of green energy. Magnesium-based hydrogen storage materials are widely regarded as one of the most promising materials in this category owing to advantages such as high hydrogen storage capacity, low density, abundant resources of Mg, and low price. Nevertheless, these materials exhibit some disadvantageous features such as severe hydrogen absorption and desorption conditions, highly stable hydride generation, poor hydrogen absorption kinetics, and short cycle life. Mg-Ni series alloy is an important magnesium-based hydrogen storage material, and the substitution of these elements is the main method for modification of Mg-Ni alloy. In general, Mg is partly replaced by the main group metals, and the substituted components are often less readily hydrogenated than Mg element. Other transition metal elements instead of Ni are selected to easily stabilize the components of the original compounds. Elemental substitution improves the performance of Mg-based alloys in mainly two aspects; the thermodynamic and kinetic properties of hydrogen absorption and desorption from the gaseous to the solid phase of the magnesium-based alloy and the electrochemical properties of the alloy electrode. The hydrogen storage property of the alloy can also be improved by preparation of suitable materials. The mechanical alloying method can prolong the cycle life greatly, and the maximum amount of hydrogen absorption and desorption can be improved obviously by mechanical ball milling and solid phase sintering technology.

1.2 Understanding of engineering research focus

1.2.1 Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors

Supercapacitors are chemical energy storage devices that exhibit advantages of high power density, high charge-discharge rate, and long cycle life. The safety performance of supercapacitors is even higher than that of lithium-ion batteries, which makes them more attractive alternatives for applications in the areas of energy, power grids, and electrical vehicles. However, the relatively low energy-storage density still limits their application, and the electrode material is the key component which mainly determines the performance of supercapacitor. In order to meet the requirements of rapid charge and discharge for large currents, the electrode materials should have large specific capacity and low internal resistance. Additionally, the electrode materials should also possess good chemical and mechanical stability, as well as excellent electron and ion transport properties. A mixture of aqueous sulfuric acid solution and ruthenium dioxide has been successfully used as a metallic oxide for applications as a supercapacitor, albeit the cost of ruthenium is too high for this material to be commercialized. Hence, the possible use of other cheap transition metal oxides such as cobaltous oxide, manganese oxide, nickel oxide, and their mixtures has become the new research hotspot. The research emphasis is laid on the preparation technology and structure optimization of the electrode materials for future use as supercapacitors. Meanwhile, it is important to develop large-scale preparation methods for new and high-performance materials, in order to produce mobile power technology that is low-cost, high-performance, and shows good stability.

The main countries or regions and institutions that have produced core papers in the focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" since 2011 are listed in Table 1.2.1 and Table 1.2.2, respectively. The collaboration network among different countries or regions and institutions are illustrated in Figure 1.2.1 and Figure 1.2.2. The main countries or regions and institutions relating to the citing core papers are summarized in Table 1.2.3 and Table 1.2.4. China, Singapore, and the USA are the top three countries. It is noteworthy that the number of core papers produced in China is even larger than the sum of other countries and regions (Table 1.2.1), indicating that the research area of $NiCo_2O_4$ nanoarrays has become a hotspot in China. Nanyang Technological University in Singapore acts as the institution that is the most productive in this research topic. As for the number of core papers cited by core papers, China and Nanyang Technological University become the most productive country and institution, respectively.

Recent research content about the focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors" includes the development of a controllable microstructure of $NiCo_2O_4$, its composites with carbon materials, and specifically oriented growth with a conductive substrate. The key point for future developments is the preparation of modified $NiCo_2O_4$ nanoarrays loaded onto a three-dimensional network conductive substrate. In addition, further research is required on understanding the relationship between the microstructure and properties of these materials. Meanwhile, some unified evaluation criteria should be established so that the supercapacitors are utilized for more and better applications.

1.2.2 Gas separation membranes

Gas separation using membrane technology can be conducted at ambient temperatures and is free of phase changes when gas mixtures are separated. Compared with conventional technologies such as adsorption, absorption, and cryogenic separation, gas separation membrane technology has distinct competitive advantages in economic and environmental aspects, and has attracted significant attention worldwide. The core of gas separation membrane technology is the membrane materials. The commonly used polymer membrane materials are subject to a trade-off between permeability and selectivity: Highly permeable membranes lack high selectivity and vice versa. PIM membranes can break the permeability-selectivity trade-off to some extent, i.e., these membranes exhibit both high permeability and high selectivity. Thermal rearrangement is a common method to prepare PIM membranes. Thermally rearranged polymers are a type of glassy microporous polymers, which possess superior thermal and physicochemical stabilities. Thermally rearranged polymer membranes (TR membranes) hold great promise in gas separation field. Such membranes usually have a high fractional free volume and narrow free volume cavity distribution, and thus exhibit high gas permeability. Thermal rearrangement is an important

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	35	72.92%	4358	63.33%	124.51	2	0
2	Singapore	11	22.92%	3561	51.75%	323.73	0	0
3	USA	4	8.33%	841	12.22%	210.25	0	0
4	Taiwan of China	3	6.25%	130	1.89%	43.33	0	0
5	Korea	1	2.08%	74	1.08%	74.00	0	0
6	England	1	2.08%	53	0.77%	53.00	0	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus “Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Nanyang Technol Univ	10	20.83%	3506	50.95%	350.60	0	0
2	Cent S Univ	6	12.50%	274	3.98%	45.67	1	0
3	Tum Create Ctr Electromobil	4	8.33%	1070	15.55%	267.50	0	0
4	Anhui Univ Technol	4	8.33%	691	10.04%	172.75	0	0
5	Nanjing Univ Aeronaut & Astronaut	4	8.33%	691	10.04%	172.75	0	0
6	Zhejiang Univ	3	6.25%	733	10.65%	244.33	0	0
7	Harbin Inst Technol	3	6.25%	131	1.90%	43.67	0	0
8	“Tsing Hua Univ”, Taiwan of China	3	6.25%	130	1.89%	43.33	0	0
9	Georgia Inst Technol	2	4.17%	374	5.44%	187.00	0	0
10	Chinese Acad Sci	2	4.17%	294	4.27%	147.00	0	0

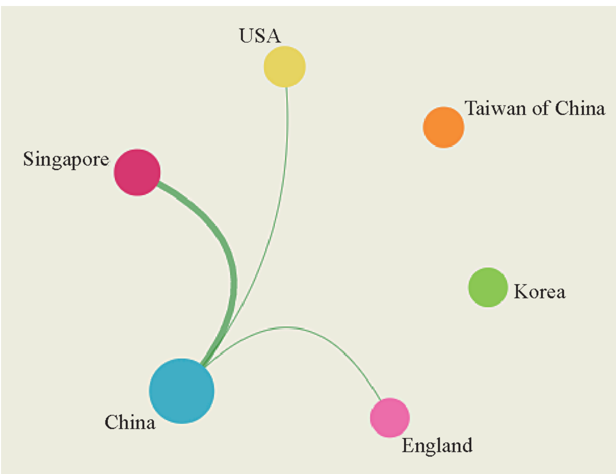

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus “Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors”[1]

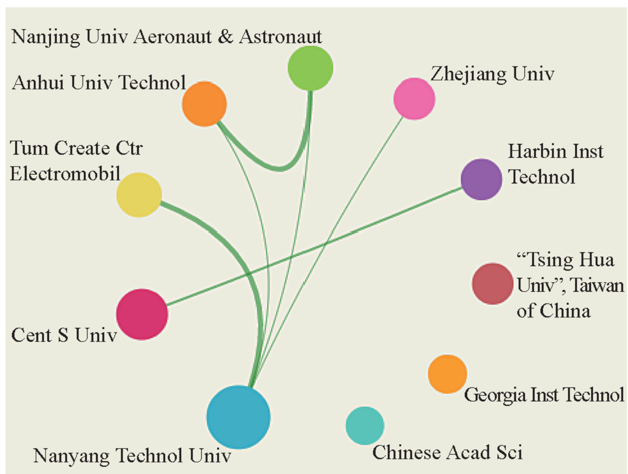

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus “Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors”

technique for polymer modification and involves conversion of the precursor polymers into rigid polymers via thermal reaction. For specific separation systems, tuning the size and distribution of free volume cavity can be implemented by the rational design of the molecular structure of precursor polymers.

The preparation of PIM and TR membranes primarily involves the polymer materials science and engineering discipline, whereas the application of membrane in gas separation is a subdivision of the chemical engineering discipline. To some extent, PIM membranes can be regarded as organic molecular sieving membranes which follow the core principles of molecular sieving, solution-diffusion, and facilitated transport mechanisms. The application of PIM and TR membranes in gas separation can be expected to break the trade-off between membrane

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	32	68.09%	2013.34
2	Singapore	10	21.28%	2012.50
3	USA	3	6.38%	2013.00
4	England	1	2.13%	2014.00
5	Taiwan of China	1	2.13%	2013.00

Table 1.2.4 Major producing institutions of core papers that are cited by core papers in the engineering research focus "Preparation of $NiCo_2O_4$ nanoarrays and their application as supercapacitors"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Nanyang Technol Univ	9	12.50%	2012.33
2	Cent S Univ	6	8.33%	2014.00
3	Tum Create Ctr Electromobil	4	5.56%	2012.75
4	Anhui Univ Technol	4	5.56%	2012.50
5	Nanjing Univ Aeronaut & Astronaut	4	5.56%	2012.50
6	Harbin Inst Technol	3	4.17%	2014.00
7	Zhejiang Univ	3	4.17%	2012.67
8	Donghua Univ	2	2.78%	2013.50
9	Georgia Inst Technol	2	2.78%	2013.00
10	Huazhong Univ Sci & Technol	2	2.78%	2013.50

permeability and selectivity. Currently, the critical issues that require solving in PIM gas separation membrane technology are methods for structural manipulation and modification of these membranes. Structural manipulation primarily involves altering the rigidity of the benzene ring linking chains, adjusting the rotation angle and the distance between adjacent rotation angles, and incorporating substitution groups in the side chains. Such manipulations are aimed at improving the diffusion and dissolution behavior of gas molecules in the PIM membrane. The modification of PIMs mainly encompasses chemical crosslinking and physical blending. It is worth noting that the materials suitable as PIM and TR membranes are quite limited at present. Therefore, future research should be centered on developing monomers with higher rigidity and higher solubility toward specific gas molecules. In addition, it is necessary to explore more facile and controllable modification methods, in order to dramatically enhance the gas separation performance of PIM membranes. Owing to the short research history of PIM and TR membranes, the whole chain design and innovation in type of membrane materials, preparation methods, structural manipulation, structure-performance relationships, and performance intensification should be carried out. It is expected that through abovementioned efforts, the gas separation performance of PIM and TR membranes can be elevated significantly. Consequently, PIM and TR membranes may be expected to gain critical relevance in the fields of energy, environment, and resources.

The primary countries or regions and institutions that have core papers published in the focus "Gas separation membranes" since 2011 are listed in Table 1.2.5 and Table 1.2.6. The scientific collaboration of the primary countries or regions and institutions is illustrated in Figure 1.2.3 and Figure 1.2.4, while the data for the citing core papers is listed in Table 1.2.7 and Table 1.2.8. Among them, Korea, the USA, Italy, and Saudi Arabia rank as the top four in the production of core papers. Except Saudi Arabia, the other nine countries or regions in the top 10 collaborate scientifically, and such collaboration between China and Korea is very active. The core paper amount from Hanyang University of Korea ranks the first. In China, the majority of core papers are from the Chinese Academy of Sciences. There is no significant difference in the ranking of the primary countries or regions and institutions producing core papers cited by core papers and that producing core papers.

1.2.3 Application of composite adsorbents for wastewater treatment

Composite adsorbents are usually made from two or more than two different materials. Several physical or chemical methods have been developed to impart new properties to the adsorbents. Different materials in composite adsorbents can complement each other in performance and produce synergistic effects. Upon combination, their properties are significantly improved. In the field of wastewater treatment, main research focuses on the visual detection and adsorption of heavy metal ions such as Hg(II), Cu(II), Zn(II), Pb(II), As(V), Co(II); lanthanide ions such as Ce(III), Eu(III), Sm(III), Nd(III), Yb(III); radioactive elements such as Cs(137); noble metal ions such as Au(III), Pd(II), Se(IV); and phosphates. These composite adsorbents can be classified into two types, namely, ion exchange resins and mesoporous silica

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus “Gas separation membranes”

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Korea	19	38.78%	785	40.19%	41.32	1	1
2	USA	11	22.45%	340	17.41%	30.91	1	0
3	Italy	9	18.37%	497	25.45%	55.22	0	0
4	Saudi Arabia	9	18.37%	271	13.88%	30.11	0	0
5	China	9	18.37%	182	9.32%	20.22	0	0
6	Wales	6	12.24%	490	25.09%	81.67	0	0
7	Australia	4	8.16%	120	6.14%	30.00	0	0
8	Scotland	4	8.16%	92	4.71%	23.00	0	0
9	Spain	4	8.16%	91	4.66%	22.75	0	0
10	England	3	6.12%	77	3.94%	25.67	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus “Gas separation membranes”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Hanyang Univ	19	38.78%	785	40.19%	41.32	1	1
2	Univ Calabria	9	18.37%	497	25.45%	55.22	0	0
3	Cardiff Univ	8	16.33%	529	27.09%	66.13	0	0
4	King Abdullah Univ Sci & Technol	8	16.33%	259	13.26%	32.38	0	0
5	Univ Texas Austin	8	16.33%	232	11.88%	29.00	1	0
6	Univ Notre Dame	5	10.20%	176	9.01%	35.20	0	0
7	Chinese Acad Sci	5	10.20%	110	5.63%	22.00	0	0
8	Hunan Univ Arts & Sci	4	8.16%	122	6.25%	30.50	1	0
9	Univ Edinburgh	4	8.16%	92	4.71%	23.00	0	0
10	Spanish Nat Res Coun	4	8.16%	91	4.66%	22.75	0	0

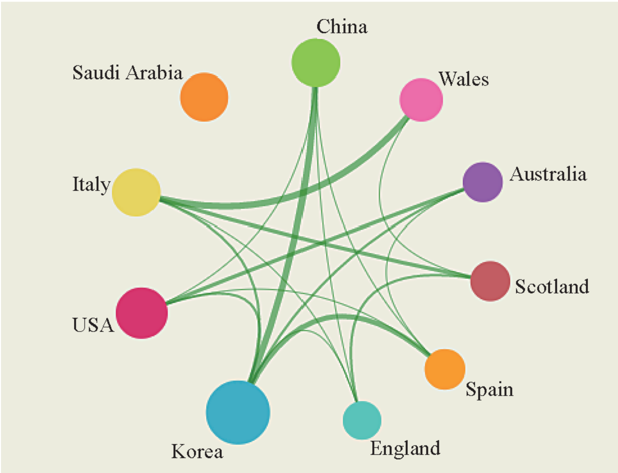

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus “Gas separation membranes”

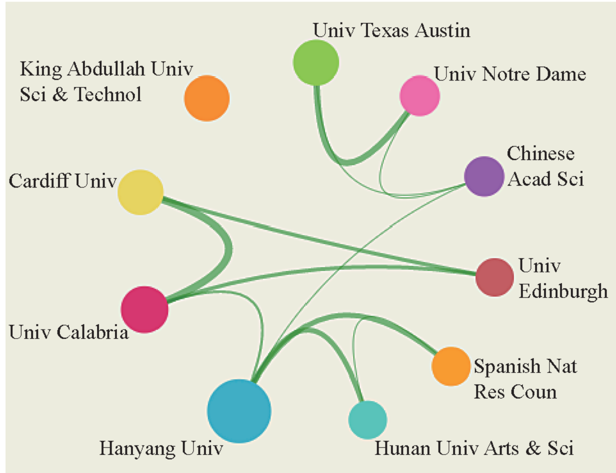

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus “Gas separation membranes”

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus “Gas separation membranes”

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Korea	16	21.62%	2013.88
2	Italy	9	12.16%	2013.89
3	China	9	12.16%	2014.56
4	Saudi Arabia	8	10.81%	2014.13
5	USA	8	10.81%	2014.00
6	Wales	5	6.76%	2013.20
7	Scotland	4	5.41%	2014.25
8	Spain	4	5.41%	2013.50
9	England	3	4.05%	2013.67
10	Australia	3	4.05%	2013.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus “Gas separation membranes”

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Hanyang Univ	16	16.67%	2013.88
2	Univ Calabria	9	9.38%	2013.89
3	Cardiff Univ	7	7.29%	2013.43
4	King Abdullah Univ Sci & Technol	7	7.29%	2014.00
5	Univ Texas Austin	6	6.25%	2014.17
6	Chinese Acad Sci	5	5.21%	2014.00
7	Spanish Nat Res Coun	4	4.17%	2013.50
8	Hunan Univ Arts & Sci	4	4.17%	2015.25
9	Univ Notre Dame	4	4.17%	2014.00
10	Univ Edinburgh	4	4.17%	2014.25

materials functionalized by organic compounds. The adsorbents and the technologies for their functionalization by organic compounds are decided according to the characteristics of the adsorbed ions.

For the adsorption treatment of phosphate containing wastewater, weak-base anion-exchange resin fibers and selective ligand exchange adsorbent fibers such as poly(vinylamine) chains grafted onto polypropylene fiber are preferentially used as adsorbents. These absorbents can selectively absorb phosphate at high feed flow rates, and do not show other ion interferences.

For the adsorption treatment of Hg(II), Cu(II), Zn(II), Pb(II), As(V), Co(II), and other heavy metal ions, the absorbents should allow visual detection, and demonstrate highly efficient adsorption at low cost. These absorbents must be able to simultaneously selectively detect and remove ions. For this purpose, research should focus on achieving rapid visual detection and highly efficient adsorption of heavy metal ions from wastewater so as to reach drinking water quality standards. At present, main references of this research field originate from the Japan Atomic Energy Agency. They have focused on using mesoporous SiO_2 as an adsorbent carrier and introduced different organic compounds to selective adsorb heavy metal ions in addition to pH sensitivity. The organic compounds used for functionalization of the adsorbents usually have N-containing heterocyclic structures, carboxylic acid groups, carbon-nitrogen double bonds, and nitrogen-nitrogen bonds. Such organic compounds adsorb heavy metal ions by forming metal-ligand complexes and after adsorption of the aforementioned metal ions, the absorbents can be washed by acids to recover the metal elements as well as the adsorbents.

For the adsorption of radioactive element Cs(137), dibenzo-18-crown-6 ether was immobilized onto mesoporous silica monoliths as an adsorbent. This conjugate adsorbent showed high adsorption efficiency and could be reused several times after recovery. For the rapid visual detection and absorption of lanthanide ions such as Ce(III), Eu(III), Sm(III), Nd(III), and Yb(III), organic ligands 4-tert-octyl-4-((phenyl)diazenyl)phenol, 4-dodecyl-6-((4-(hexyloxy)phenyl)diazenyl) benzene-1,3-diol, *N*-methyl-*N*-phenyl-1,10-phenanthroline-2-carboxamide, which contain O and N donor atoms, were synthesized and subsequently immobilized onto mesoporous silica material. These adsorbents showed rapid visual detection of lanthanide ions in water and could adsorb even ultra-trace amounts of these ions from aqueous solutions.

From 2011, the main countries or regions and institutions producing core papers in the research focus "Application of composite adsorbents for wastewater treatment" are listed in Table 1.2.9 and Table 1.2.10, as well as the collaboration networks of the main countries or regions and institutions are shown in Figure 1.2.5 and Figure 1.2.6. The main countries or regions and institutions to cite these core papers are summarized in Table 1.2.11 and Table 1.2.12. Among them, the research on composite adsorbents mainly focuses on inorganic mesoporous silica materials that have been functionalized by organic ligands. These core papers mainly came from eight countries or regions, and Japan ranked the first, having published 46 core papers, while Bangladesh ranked the second with 17 core papers. It is worth noting that the collaboration in this area is primarily between Japan and Bangladesh. Furthermore, Japan also cooperates with Egypt and Saudi Arabia; and Egypt, Saudi Arabia, and Bangladesh also cooperate with each other. The most of the published papers came from Japan Atomic Energy Agency (ranking the first), the second is Shaheed Ziaur Rahman Medical College of Bangladesh. These institutions mainly cooperate with Japan Atomic Energy Agency. Besides the institutions of Bangladesh and Saudi Arabia, other countries or regions also cooperate with each other. The main countries or regions and institutions to cite these core papers are the top five such countries or regions that also publish these papers, with Japan ranking the first. Among the top 10 institutions producing core papers cited by core papers, eight are the main institutions producing these core papers.

The application and research of composite adsorbents for wastewater treatment is one of the more recent research hotspots. It is expected that in the following couple of decades, many research papers and work will focus on this research field. For highly sensitive and visual detection of metal ions, highly efficient and specific absorbents will likely make significant progress. The research and development will mainly focus on the aspects of engineering research in the different application fields based on the laboratory results.

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan	46	95.83%	1577	96.10%	34.28	10	0
2	Bangladesh	17	35.42%	510	31.08%	30.00	1	0
3	Egypt	10	20.83%	359	21.88%	35.90	2	0
4	Saudi Arabia	6	12.50%	141	8.59%	23.50	2	0
5	Australia	2	4.17%	44	2.68%	22.00	0	0
6	Korea	1	2.08%	69	4.20%	69.00	1	0
7	India	1	2.08%	33	2.01%	33.00	0	0
8	Taiwan of China	1	2.08%	31	1.89%	31.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Japan Atom Energy Agcy	42	87.50%	1427	86.96%	33.98	9	0
2	Shaheed Ziaur Rahman Med Coll	12	25.00%	317	19.32%	26.42	1	0
3	Natl Inst Mat Sci	8	16.67%	405	24.68%	50.63	3	0
4	Independent Univ	8	16.67%	253	15.42%	31.63	1	0
5	Kumamoto Univ	6	12.50%	273	16.64%	45.50	2	0
6	King Saud Univ	6	12.50%	141	8.59%	23.50	2	0
7	Sohag Univ	4	8.33%	162	9.87%	40.50	2	0
8	Univ Dhaka	4	8.33%	159	9.69%	39.75	0	0
9	Suez Univ	4	8.33%	122	7.43%	30.50	0	0
10	Waseda Univ	3	6.25%	96	5.85%	32.00	0	0

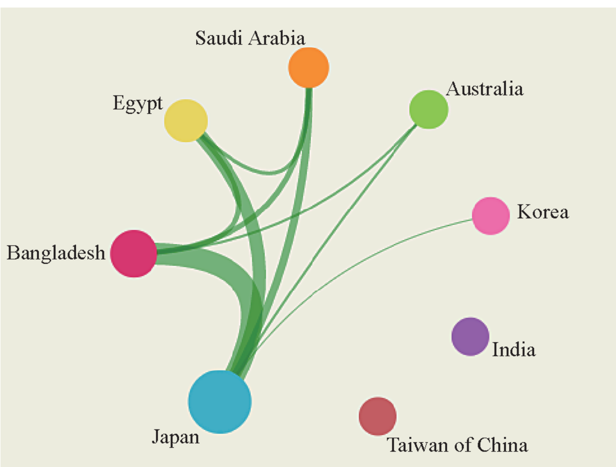

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

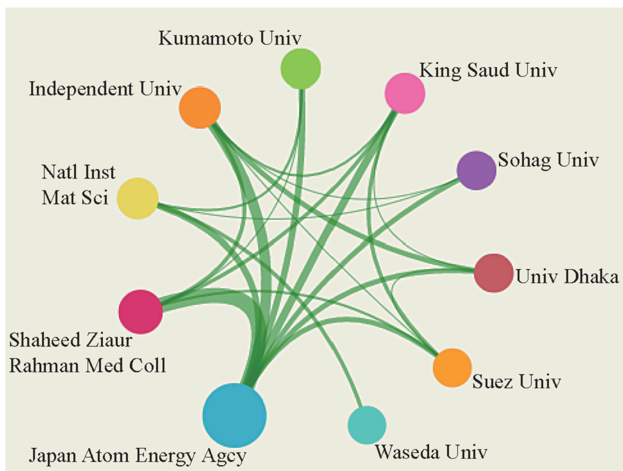

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	Japan	41	53.95%	2014.37
2	Bangladesh	17	22.37%	2014.65
3	Egypt	10	13.16%	2014.00
4	Saudi Arabia	6	7.89%	2015.17
5	Australia	2	2.63%	2015.00

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Application of composite adsorbents for wastewater treatment"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Japan Atom Energy Agcy	41	44.09%	2014.37
2	Shaheed Ziaur Rahman Med Coll	12	12.90%	2014.83
3	Independent Univ	8	8.60%	2014.75
4	King Saud Univ	6	6.45%	2015.17
5	Kumamoto Univ	4	4.30%	2013.25
6	Suez Univ	4	4.30%	2014.75
7	Univ Dhaka	4	4.30%	2014.25
8	Sohag Univ	3	3.23%	2014.00
9	Curtin Univ	2	2.15%	2015.00
10	Elec Power Res Inst	2	2.15%	2012.50

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top nine engineering development hotspots in the disciplines of chemical, metallurgical, and materials engineering assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. Table 2.1.2 shows the annual number of core patents that have been published in recent years. Among these nine engineering development hotspots, "New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials" and "Development and application of new energy technologies" belong to the field of energy and its relevant technologies; while "Optimized design, preparation, and applications of novel thin films and thin-film devices," "Preparation and properties of graphene," and "Preparation and applications of nanomaterials" also partly belong to the subgroup of energy, indicating the importance of the energy issue in the current world. The average citation for each core patent exceeds 10 and their average publication year is 2012. Some experts believe that "Optimized design, preparation, and applications of novel thin films and thin-film devices," "Preparation and properties of graphene," "Biodegradable medical devices & health monitoring," and "Preparation and applications of nanomaterials" are the new and emerging development hotspots while others discussed in this category are merely further developments of the more traditional subject areas.

(1) Optimized design, preparation, and applications of novel thin films and thin-film devices

With the development trend of miniaturization and

Table 2.1.1 Top 9 engineering development hotspots in chemical, metallurgical, and materials engineering

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Optimized design, preparation, and applications of novel thin films and thin-film devices	704	10 607	15.07	2012.22
2	Preparation and properties of graphene	43	1 181	27.47	2011.70
3	Preparation and applications of aluminum, magnesium, and titanium light metal alloys	285	2 856	10.02	2012.51
4	Biodegradable medical devices & health monitoring	92	3 384	36.78	2012.48
5	New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials	258	4 435	17.19	2011.74
6	Preparation and applications of nanomaterials	172	1 954	11.36	2012.23
7	Preparation techniques for advanced resin matrix composites	169	3 194	18.90	2012.02
8	New technology of iron and steel clean production and development of high-performance steel	413	4 366	10.57	2012.17
9	Development and application of new energy technologies	41	1 128	27.51	2011.85

Table 2.1.2 Annual number of core patents belonging to each of the top 9 engineering development hotspots in chemical, metallurgical, and materials engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Optimized design, preparation, and applications of novel thin films and thin-film devices	276	186	121	63	45	13
2	Preparation and properties of graphene	26	6	9	2	0	0
3	Preparation and applications of aluminum, magnesium, and titanium light metal alloys	74	68	85	43	12	3
4	Biodegradable medical devices & health monitoring	31	16	23	15	6	1
5	New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials	133	72	45	5	2	1
6	Preparation and applications of nanomaterials	59	40	50	21	1	1
7	Preparation techniques for advanced resin matrix composites	69	54	29	10	5	2
8	New technology of iron and steel clean production and development of high-performance steel	141	112	116	37	6	1
9	Development and application of new energy technologies	21	11	5	2	2	0

integration in the field of electronics, there is an urgent need for advanced functional and structural thin films in several fields such as national defense, aviation aerospace, automobile engines, and even in all walks of the national economy. In particular, optical thin films, magnetic thin films, silicon thin films, thermoelectric thin films, piezoelectric thin films, transparent films, superhard films, and organic films have all attracted significant attentions. By optimizing the design and deposition methods of the thin film preparation process (such as chemical vapor deposition or physical vapor deposition), the synergy of advanced micro-fabrication technique can finally realize the application of micro sensors, micro actuators, micro mechanical structures, micro power supplies, and signal and control circuit processors. Research of thin films and thin-film devices is also very crucial for national development and security.

(2) Preparation and properties of graphene

Graphene has an ideal two-dimensional crystal structure with a single atomic layer, which is composed of a hexagonal lattice. The particularity of graphene structure leads to some unique mechanical, thermal, and electrical properties. Graphene-based materials are prospective candidates for broad applications and have been used as solar battery electrode materials, super capacitors, hydrogen storage materials, lithium ion battery electrode materials, and optical materials. Such materials are foremost in the category of emerging materials and research on graphene and graphene-based materials has entered a stage of rapid development. Several countries have regarded the preparation of graphene and its application technology as a long-term strategic development direction, aiming to occupy the leading position in the industrial revolution. However, in the practical preparation, graphene is not stable and easy to reunite, which limits the use of the excellent properties of single layer structure of graphene materials. The key bottleneck for the widespread use of graphene is the dispersion technology. Graphene oxide is an important foundation for the preparation of functionalized graphene materials, and the process of preparation is simple, low-cost, and easy to modify. Thus, high-quality and large-scale preparation of graphene materials is the foundation of all future applications. The development of a simple, controllable chemical method to fabricate graphene on a large scale is the most convenient and feasible way.

(3) Preparation and applications of aluminum, magnesium, and titanium light metal alloys

With the rapid development in high technologies such as aerospace, nuclear power, automobile, and biology medical treatment, the demand for high-performance light metal alloys has increased remarkably. A great deal of work focused on light alloys of aluminum, magnesium, and titanium has been carried out. This important field includes high-performance aluminum alloys for use in structures and wires owing to their high strength and high toughness, magnesium alloys for their wear and corrosion resistance, biodegradability and biocompatibility, and titanium alloy materials for use in energy and medical devices. Significant attention has been paid to the development of high-performance aluminum alloys for their use in conductors in order to reduce the industrial cost arising from the price factor of the copper raw material. Research and development of high-performance aluminum alloys as structural materials has been the focus of aerospace and automotive fields. In contrast, magnesium alloys still cannot meet the requirements of strength, toughness, and corrosion resistance for application as structural materials. The development of magnesium alloys with the above-mentioned attributes still needs a long time. Meanwhile, biodegradable magnesium alloys have become the focus of research in recent years because magnesium-based devices circumvent the adverse effects that are ordinarily caused by foreign objects staying in the body for a long time after the implantation of inert medical metal materials such as stainless steel and titanium alloy. The focus of research and development of biomedical magnesium alloys is mainly to control the composition and microstructure of alloys such that the alloy demonstrates good comprehensive properties of mechanics, corrosion, degradation, and biocompatibility, and meets the needs of clinical applications.

(4) Biodegradable medical devices & health monitoring

With the accelerating trend of population aging and the rapidly increasing demand for medical care, it is imperative to develop next-generation, revolutionary biomedical implants and medical devices that are biodegradable or bioresorbable in the human body. These efforts aim to address the current clinical challenges such as chronic inflammation and secondary surgeries, which are associated with the use of conventional permanent implants, in order to significantly improve treatment efficacy and alleviate the suffering of patients. The research and development components of biodegradable medical devices mainly include computational design and development of novel biodegradable biomaterials, optimum structure design and precision processing for medical devices, surface modification and functional coating design and preparation, and *in vitro* and *in vivo* degradation and evaluation of biosafety and efficacy. Developments in these areas may help to achieve the integration of controlled degradation, good biocompatibility, and other adaptive functions for typical types of biodegradable medical devices. In addition, aiming at the key problems of heart failure and orthopedic disease in China's aging society, health monitoring and forecasting has become a main research focus area. With intelligent materials as the core technology, it is attractive to perform research on wearable, rapid monitoring equipment, targeted therapy, drug carriers, and artificial tissues for key intelligent materials and devices.

These advances would realize miniaturization, multifunctionality, and rapid detection toward key diseases.

(5) New electrochemical energy storage materials and system R&D technologies, power lithium ion batteries, and other high-performance energy storage materials

With the looming energy crisis and environmental problems such as haze and global warming, new electrochemical energy storage technologies have attracted more attention than ever. The development of energy storage devices has become an important research direction. Specifically, it is of urgent interest to develop energy storage devices with high specific capacity, high specific energy, long life, safe operation, and low cost. The energy storage systems that meet these requirements include solid state lithium ion batteries, high voltage positive electrode-metal lithium negative batteries, lithium sulfur batteries, lithium air batteries, sodium sulfur batteries, supercapacitors, and so on. The material employed in these energy storage devices is one of their most important components and also the key factor that determines their performance. The key technologies related to such materials mainly include controlled synthesis of nanostructured electrode materials, investigation of the electrochemical reaction mechanism, development of new electrolyte materials, study of Li-ion transport mechanism and electrolyte-electrode interface stability, light-weight technology, safety optimization of the storage systems, and so on. The energy storage devices using new materials with superior electrochemical performance will have broad applications in the fields of electric vehicles, consumer electronics, home energy storage, and utilization of renewable energy.

(6) Preparation and applications of nanomaterials

Nanotechnology has brought together modern multidisciplinary fields of science at the nanoscale, and is one of the largest and most competitive research areas worldwide. Nanomaterials are one of the current focuses and frontiers in the field of materials science, and at present, most countries have declared production and technology development of nanomaterials as an important research field. The properties of the nanomaterials (scale of 1–100 nm) are studied in terms of atomic and molecular level interactions. The goal of such studies is to manipulate the atoms, molecules, and substances such that they show novel physical, chemical, and biological characteristics, and can be used to produce materials with specific functions. The six primary aspects of such studies are: ① preparation and processing technology of new nanomaterials; ② nano characterization and standards; ③ nano biomedicine; ④ nano information materials and devices; ⑤ energy nanomaterials and technologies; ⑥ environmental nanomaterials and technologies. Nano materials are widely used in diverse fields such as nano ceramic materials, nano semiconductor materials, nanocatalytic materials, nanomedicine, and carbon nanotubes. Thus, the field of nanomaterials and integration design, from basic research to application research, is expected to achieve major breakthroughs in the important application areas of nanotechnology.

(7) Preparation techniques for advanced resin matrix composites

Advanced resin matrix composites are prepared by compound techniques. They are a combination of organic polymers acting as the matrix and high-performance fibers that act as reinforcing materials. These composites are advanced materials with properties that are remarkably better than those of the original components. They have been widely utilized in aerospace, national defense, and military industries, as automobile, mechanical and electrical apparatus, and in the field of healthcare. In aerospace engineering applications, advanced resin matrix materials display many advantages such as high specific strength and specific stiffness, excellent corrosion resistance, structure dimension stability, and convenience in large-scale integrated shaping. Currently, advanced resin matrix composites are the fourth largest aerospace structural materials after aluminum, steel, and titanium. They are mainly used in structural components of airplanes and helicopters, airborne radomes, artificial satellites, space stations, airproof adhesives, and space transportation systems. In the automobile manufacturing field, advanced resin matrix composites are extensively utilized to enhance the performance of vehicles. The demand of this material is also very extensive in the field of mechanical and electrical apparatus industry, for example, as blowers and engineering machinery. Besides, with the rapid development of integration technology, the working frequency of electronic components has increased dramatically, and the demand of integrating thermal conductivity on the interface in addition to water and thermal resistance of printed circuit boards has increased. Similarly, ion exchange resins and other advanced resin-based materials have been employed in medical treatment, e.g., for manufacturing artificial hearts, respirators, and stents. Nowadays, advanced resin matrix materials are being developed with high performance as the key attribute, such as using high-performance fibers to strengthen the comprehensive properties of the composites, increasing their weight reducing efficiency, establishing its manufacturing standards, achieving intelligent production, as well as developing low-cost preparation technologies.

(8) New technology of iron and steel clean production and development of high-performance steel

In recent years, with the rapid development of high-speed rail, automobile, shipping, and mechanical industries, the demand of high-strength steel has become more and more exuberant. The key topics in this field include studies on developing a short and clean process in iron and steel metallurgy, involving the purification process and improvements in equipment handling molten steel and the optimization of slag type, as well as special steel, clean steel, and corrosion resistance steel in marine engineering. In the field of the high-performance steel, following objectives can be outlined: ① developing special steel for strategic applications such as national thermal and nuclear power generation, including supercritical heat resistant steel and manufacturing techniques of AP1000 forge piece; ② developing steel for energy, aviation, and marine applications which can bear high/low temperature, high pressure, or a complex medium; ③ developing high-strength and high-toughness steel in addition to corrosion resistant double metal composites, including its rolling technology and equipment; ④ preparation of high-quality heavy plate and large-scale castings and forgings with high cleanliness; ⑤ study of new strengthening and toughening mechanisms and reliable long-life mechanism of special steel, the evolution of microstructures during the preparation and service processes, the material design technique which incorporates resistance to high temperature, stress, and corrosion; ⑥ high-cleanliness smelting and quality control techniques for special steel, precise control of inclusions, homogenization and fine control of tissue, precision forming, and processing; ⑦ low-cost production and simplification of the process. The design of the entire process of iron and steel making has to be updated, with clean energy and raw materials, and advanced techniques and equipment also need to be adopted. Other measures need to be employed to improve efficiency at the management level and enable a comprehensive utilization of resources, lower the environmental pollution, enhance resource utilization efficiency, and realize a clean production of steel and iron.

(9) Development and applications of new energy technologies

With the arrival of the post-petroleum world, the energy security and environmental problems have become increasingly acute. Against this background, there is an urgent need for innovative technologies to cope with issues such as coal gasification, biomass pyrolysis and deoxidization, reclamation of inferior or heavy oil, methanation of syngas, and nuclear power. The key to achieving a successful application of new energy technologies is to develop new equipment and processes to solve problems such as the *in situ* regeneration of catalysts and integrated utilization of waste heat, which are brought by the complexity of feedstock and high process temperatures. Among these research focuses of innovative energy technologies, although coal gasification and the methanation of syngas have been realized, the demand-supply gap is greater than 40%, these technologies are running with high costs. The resource utilization of inferior or heavy oil has been realized in some industrial plants but the technical maturities are not sophisticated enough for mass production. Researches on biomass pyrolysis and deoxidization are still in their early developmental stage. Therefore, the technologies including the novel gasifier and coking furnace, the process coupling the petroleum cracking and biomass pyrolysis, and the exploitation of catalytic cracking of biomass are the research hotspots.

2.2 Understanding of engineering development focus

2.2.1 Optimized design, preparation, and applications of novel thin films and thin-film devices

With the development trend of miniaturization and integration in the electronics, thin films and thin-film devices, as well as their processing techniques have had a significant effect on the wide field of high technological industry, in the forms of large scale integrated circuits, flat-panel displays, electronic components, information recording and storage, microsensors, and thin-film solar cells. Hence, research of thin films and thin-film devices is crucial as it relates to the national development and security.

Thin-film technology has been included in the medium- and long-term development plans of many developed countries. In the USA, it tends to be applied mainly in the military and aerospace field. Japan has a leading role in the use of high-technology products. The EU emphasizes the applications of small power sources, sensors, and products with nanotechnology. As for the research of thin-film materials, while China is in the top list, there still exists a big gap in the research of new thin films and thin-film devices compared with developed countries. Therefore, it is urgent to implement industrialization of new thin films and thin-film devices in China

The different branches of engineering techniques relating to thin-film technology are as follows.

(1) Solar thin films. With the rapid development of solar photovoltaic technology, thin-film solar cells with their unique advantages and mature technology have gradually occupied the entire photovoltaic market at a tremendous growth rate. However, efficient fabrication technologies and thin-film materials are still the bottle neck of large-scale production, which demand that the following challenges be addressed for the development of thin film solar cells: ① lack of deep understanding of some physical science problems; ② making further improvement on existing technologies; ③ using new materials or structures to replace the current expensive and toxic materials; ④ further investigation of precision equipment and key technologies.

(2) Thermoelectric thin films. Thermoelectric materials are well known for their ability to convert of heat into electrical energy. These materials are usually used in the preparation of micro power supplies or electronic chip cooling devices. Furthermore, they can realize quick and efficient active cooling, and achieve refrigeration and heating transformation by changing the direction of the current. Meanwhile, they can even generate electrical power using waste heat. Efficient thermoelectric conversion devices can be prepared as bulk or film materials, and these have many attractive features compared with other methods of refrigeration. These advantages include simple construction, high reliability, no emissions of toxic gases, small volume, no moving parts, and low maintenance. Studies show that the cooling power density of a thermoelectric device is inversely proportional to their size; thin-film thermoelectric devices more effectively improve the efficiency of refrigeration. Thus, research in this field requires devising methods to improve the ZT value of the existing materials system.

(3) Transparent conductive thin films. Transparent conductive oxide thin films are very important photoelectric materials with a wide forbidden bandwidth, high light transmission rate in the visible spectrum, and low resistivity. Because of their excellent photoelectric properties, they are widely used in solar batteries, liquid crystal displays, and even as gas sensors. Presently, this field has developed into new and high technology industry. Thin metal films exhibit good electrical conductivity owing to the free electrons in metals. Therefore, they may be used as transparent conductive films. Unfortunately, metal films typically exhibit poor transparency. In contrast, semiconductor and polymer films display poor electrical conductivity but good transparency. The electrical conductivity and transparency for multilayered films are both very good. The development of transparent conductive films for mass production demands a means to coordinate the requirements of conductivity and transparency. This issue is the bottleneck which restricts the widespread applicability of transparent conductive films. With the development of carbon nanomaterials and other metal-doped composite materials, the performance and applicability of transparent conductive films is likely to increase.

(4) The application of integrated thin-film device. Thin-film integrated circuits are based on thin-film materials that have a thickness of 1 μm and are fabricated by vacuum evaporation, sputtering, electroplating process, and interconnection techniques. Although the components in thin-film circuits are characterized by high precision, good temperature frequency, wide operational wave band, high integration, and small size, the process equipment is relatively expensive, which results in high production costs. Thin-film hybrid integrated circuits are applicable to all kinds of circuits, particularly analogue circuits with the requirements of high precision, stability, and high performance. Compared with other integrated circuits, it is more suitable for use as a microwave circuit. The key issues of integrated thin-film devices that arise during thin-film circuit integration are the interface between the solid-state thin film and substrate, the design compatibility with the structure of the readout integrated circuit, microfabrication process and testing technology, and growth of large-size thin films with low defect density. Compared with the USA and Japan, China has made great progress in the

production of specialty films and has reached the international top level. However, the critical thin-film components still rely on imports. Although some countries are in a leading position in this regard, their research and production is also in its nascent stages. This suggests that the innovation space is very big. Thus, China should seize the opportunities for development and design and produce a variety of integrated structure components, modules, and devices.

At present, research on thin-film materials and devices has been attracting a lot of attention. In particular, developed countries and regions such as Europe, America, Japan, and Korea have all been the leaders in the research and development of thin-film materials and devices as well as the implementation of large-scale industrialization. The basic research performed on specific thin-film materials in China is in the international leading position, but mass production is still dependent on imports. Our independent research and development ability of thin-film materials and devices is insufficient; the overall technology is also relatively immature. In addition, functional thin films are an important part of new materials in the 21st century, such as the back film and ethylene-vinyl acetate copolymer (EVA) film for solar cells, diaphragm of lithium ion battery and nickel metal hydride battery for new energy cells, and diffusion films, optical prism films, composite films, and optical films for the flat panel display, as well as electrical insulation films, semiconductor films, and microelectronics films, which are all urgently required new materials in China. Current functional film production is highly dependent on external enterprises, leading to the immense profits earned by foreign companies. In order to achieve long-term development in China, we must fully devote our attention into developing functional thin films. The manufacturing of high-end films is the future development direction in China.

The main countries or regions and institutions that have published the largest number of core patents in the focus "Optimized design, preparation, and applications of novel thin films and thin-film devices" since 2011 are shown in Table 2.2.1 and Table 2.2.2. The major collaboration networks among countries or regions and institutions are shown in Figure 2.2.1 and Figure 2.2.2. It is evident from the patent distribution of thin-film materials and devices industry that the practical patents are mainly concentrated in European countries and the USA. Although China is in the third place, our core patents, total citation, and average citation are still far behind those in the USA. Among them, the patent agencies with the maximum number of public core patents are largely concentrated in the USA. The total citations is much higher than that of other countries, suggesting that the research in the USA is highly endorsed by the global scientific research workers. Although research in China started late and has not yet been intensively supported, the study of thin-film materials and devices has seen active engagement in recent years. Data shows that great progress in this field might be anticipated, enough to obtain the topmost rank in the world.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	304	43.18%	5320	50.16%	17.50
2	Japan	165	23.44%	2060	19.42%	12.48
3	China	85	12.07%	1015	9.57%	11.94
4	Korea	71	10.09%	1286	12.12%	18.11
5	The Netherlands	34	4.83%	591	5.57%	17.38
6	Germany	17	2.41%	141	1.33%	8.29
7	Taiwan of China	17	2.41%	205	1.93%	12.06
8	France	7	0.99%	27	0.25%	3.86
9	Belgium	6	0.85%	49	0.46%	8.17
10	UK	4	0.57%	40	0.38%	10.00

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Appl Material Ltd.	80	11.36%	1848	17.42%	23.10
2	Samsung	48	6.82%	1014	9.56%	21.13
3	ASM Int Corp	40	5.68%	849	8.00%	21.23
4	Novellus Systems Inc.	39	5.54%	979	9.23%	25.10
5	LAM Res Corp	26	3.69%	385	3.63%	14.81
6	Tokyo Elect Ltd.	26	3.69%	466	4.39%	17.92
7	FUJI Film Corp	15	2.13%	84	0.79%	5.60
8	IBM Corp	11	1.56%	127	1.20%	11.55
9	Konica Minolta Inc.	10	1.42%	119	1.12%	11.90
10	Nitto	9	1.28%	43	0.41%	4.78

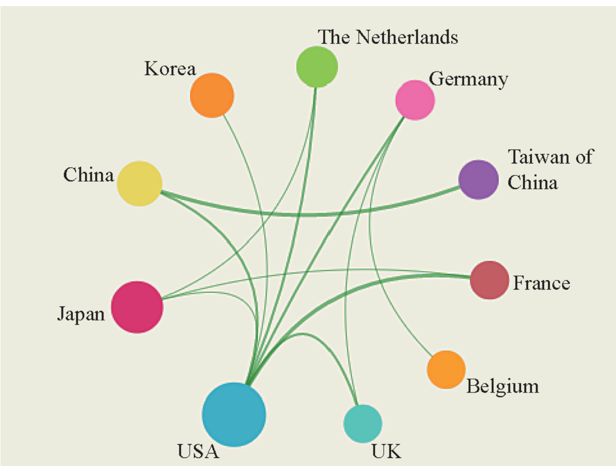

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

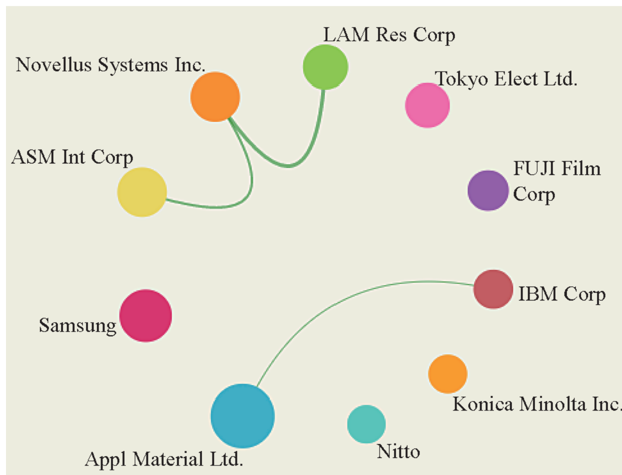

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Optimized design, preparation, and applications of novel thin films and thin-film devices"

Nevertheless, the core institution in this field still needs to be energetically supported in our country.

2.2.2 Preparation and properties of graphene

Since graphene was discovered in 2004, research on this material has been uninterrupted. Graphene is a single-layered carbon sheet with a hexagonal packed lattice structure and shows many unique properties such as quantum hall effect (QHE), high carrier mobility at room temperature (~10 000 $cm^2 \cdot (V \cdot S)^{-1}$), large theoretical specific surface area (~2630 $m^2 \cdot g^{-1}$), good optical transparency (~97.7%), high Young's modulus (~1 TPa), and excellent thermal conductivity (3000–5000 $W \cdot (m \cdot K)^{-1}$). Owing to these features, graphene has been widely applied in batteries, supercapacitors, fuel cells, solar photovoltaic equipment, photocatalysis, sensors, and Raman enhancement. Graphene is a star among the class of similar emerging materials and research on this topic has entered a stage of rapid development. In fact, many countries now regard the research direction of preparation of graphene and its application technology as crucial for long-term strategic development. These initiatives are typically undertaken with the aim of occupying the helm in the industrial revolution.

However, in practice, graphene is not stable and its layers are easily reunited during preparation. This makes it difficult to utilize the full extent of the excellent properties of single layer structure of graphene materials. The key bottleneck for wider use of graphene is the dispersion technology. The fabrication methods of graphene mainly include chemical oxidation-reduction, physical stripping, epitaxial growth, and chemical vapor deposition. Although high-quality graphene can be obtained by using the mechanical stripping method, it suffers from shortcomings of being a low yielding and time consuming process in which it is difficult to precisely control the size of graphene. Monolayers or minority layers of graphene can be fabricated via chemical oxidation-reduction method. However, the effect of strong oxidant damages the sp^2 conjugate structure of graphene, which results in its degradation. Chemical vapor deposition and epitaxial growth methods can be used to prepare high-quality and large-area graphene, but the high cost, complex technology, and strict process conditions restrict the development of graphene. To conclude, the preparation of high-yield, low-cost, and high-quality graphene is still a challenge, leading to its limited applications in the chemical, energy storage, and catalysis fields.

(1) Micro mechanical stripping method. In 2004, scientists first fabricated monolayered graphene from highly-oriented pyrolytic graphite by using the micro mechanical stripping technology. This revealed that graphene with two-dimensional crystal structure can exist. At present, this method can only be used for small-scale laboratory preparation of graphene. Although the quality of the products is very high, the disadvantage of low production rate and the high cost cannot meet the needs for large-scale industrial production.

(2) Chemical vapor deposition method. In this method, the material in the gas phase typically undergoes a chemical reaction, and the solid deposits generated on the surface of a heated substrate form the solid material. This method first achieved the large-scale preparation of graphene. It is possible to realize large-scale preparation of high-quality graphene, but the cost is too high and the process too complex.

(3) Oxidation-reduction method. Oxidation-reduction method is the best method for the preparation of graphene. It has solved the problem of dispersion with the formation of a stable graphene suspension. By reacting with a strong acid and a strong oxidant, graphite oxide is obtained using the ultrasonic disperse technology. Then by adding an appropriate reducing agent, the oxygen-containing functional groups on the surface can be effectively removed to form monolayer graphene. However, this method produces liquid waste pollution and the product may also have some defects. Such defects lead to a loss of electrical performance, which limits the application of graphene.

(4) Solution stripping method. This method involves spreading a small amount of graphite in the solvent and using ultrasonic processes to obtain a low-concentration dispersion. The graphite layer can be peeled off by destroying the interlayer van der Waals forces to obtain graphene. This method does not damage the structure of graphene, and although the quality is very high, the yield is quite low.

(5) Solvothermal method. This method has increasingly attracted because high-quality graphene can be prepared under high temperature and high pressure in the closed system. Although this method allows the preparation of graphene on a large-scale, it inevitably has a negative effect on the electrical conductivity. The combination of the solvothermal method and other preparation methods is expected to become a hotspot in the preparation of graphene.

In recent years, European countries, the USA, Japan, and other countries have started to invest in domestic graphene science and applied research. While the USA mainly focuses on the cutting-edge application of graphene. Defense Advanced Research Projects Agency has developed a graphene-based radio frequency circuit that performs at super-fast speeds and requires very less power to operate. The National Science Foundation of the USA has funded the graphene-based supercapacitor project and continuous and large-scale nano-manufacturing project. The EU has upgraded graphene to strategic importance by considering graphene research in a Future and Emerging Technologies Flagship program, aimed at achieving complete coverage of the entire value chain, from material production to components and system integration. The academia and enterprise in UK are also playing a key role in this process. In 2011, UK's *Innovation and Research Strategy for Growth* clearly outlined graphene as one of the four future focuses. The UK will support research and commercial applications of graphene, in order to guarantee their leading position in this field and transfer the material from laboratory preparation into the production line and finally to the market in the coming decades. The commercialization process of graphene is mainly promoted by the UK's National Graphene Institute. Germany mainly explores the electronic machinery products of graphene, and the German Research Foundation announced its aim of funding frontier research projects on graphene, whose goal is to improve the understanding and control of graphene properties, and develop new graphene-based electronic products. Korea has constructed a graphene alliance which consists of 41 research institutions including the Korea Advanced Institute of Science and Technology and six other enterprises. A special support fund has also been set up to help enterprises apply and commercialize graphene products and related technology. Japan has instead chosen diversification as the main direction for graphene. In 2007, the Japan Science and Technology Agency started financing graphene/silicon materials/device projects, and exploited advanced auxiliary switch devices and plasma resonance hertz devices. With increasing research into graphene and its applications, the stage for the industrialization of graphene has gradually been set.

It is important to note that graphene has a very wide range of applications. The data in this report comes from the "materials area" patent map, and the data volume and subordinate areas both have some limitations. The detailed analysis based on this data is as follows: Since 2011, the main countries or regions and institutions that have produced core patents in the focus "Preparation and properties of graphene" are shown in Table 2.2.3 and Table 2.2.4. The collaboration networks among the countries or regions and institutions are illustrated in Figure 2.2.3 and Figure 2.2.4. From the perspective of the patent distribution, graphene preparation technology is mainly concentrated in China and the USA, and the former has the largest number of patents in the world in this subject. It explains why China is ranked as the top of the world in this industry, but the average citation is lower than that of the USA. Hence, China should reinforce the fundamental preparation technology of graphene.

Based on the availability of solutions for the key problems in the preparation of graphene, we conclude that it will be more widely used in the future. It is expected that graphene might even replace silicon. Once the process of large-scale preparation of wafer-level graphene films has effective progress, graphene may become the core material of new-generation semiconductor devices, thus bringing a revolution in semiconductor technology and electronic information.

2.2.3 Preparation and applications of aluminum, magnesium, and titanium light metal alloys

The key technique to obtain high-performance aluminum, magnesium, and titanium light metal alloys is to precisely control their shapes and properties during the casting and deformation processes. The successful application of such materials depends on developing high-strength, tough, wear and corrosion resistant aluminum, magnesium, and titanium magnesium alloys.

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Preparation and properties of graphene"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	26	60.47%	689	58.34%	26.50
2	USA	9	20.93%	289	24.47%	32.11
3	Korea	3	6.98%	23	1.95%	7.67
4	Germany	2	4.65%	36	3.05%	18.00
5	Japan	1	2.33%	53	4.49%	53.00
6	Portugal	1	2.33%	22	1.86%	22.00
7	Saudi Arabia	1	2.33%	21	1.78%	21.00
8	Taiwan of China	1	2.33%	14	1.19%	14.00

Table 2.2.4 Major producing institutions of core patents on the engineering development focus “Preparation and properties of graphene”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	Chinese Acad Sci	6	13.95%	159	13.46%	26.50
2	Nanotek	4	9.30%	133	11.26%	33.25
3	Univ China Petroleum	2	4.65%	77	6.52%	38.50
4	Nanjing Tech Univ	2	4.65%	38	3.22%	19.00
5	Shanghai Jiao Tong Univ	2	4.65%	53	4.49%	26.50

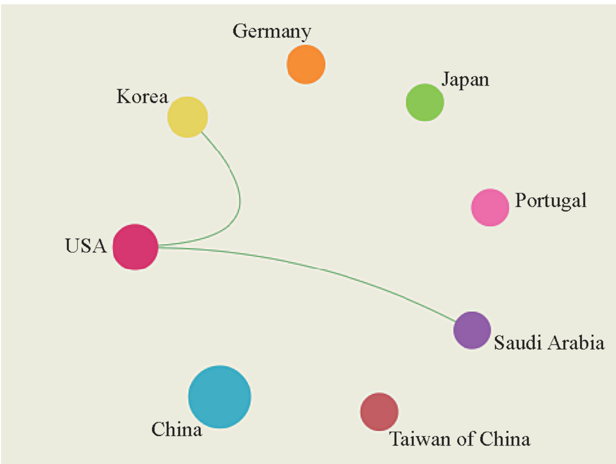

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus “Preparation and properties of graphene”

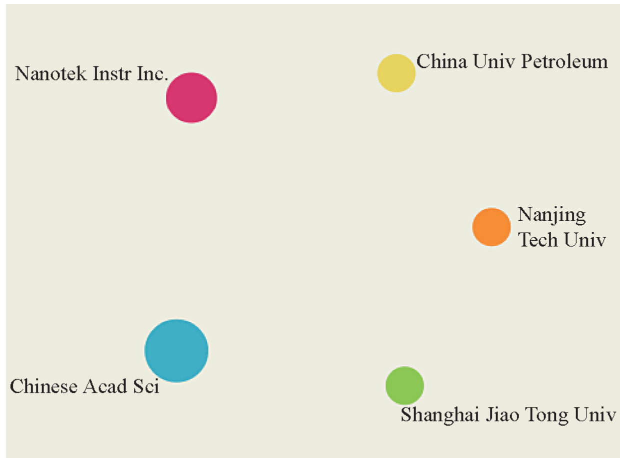

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus “Preparation and properties of graphene”

High-strength alloys typically include high-strength cast and wrought alloys. At present, the tensile strengths of the most advanced high-strength cast magnesium alloys and cast deformed magnesium alloys are > 400 MPa and > 500 MPa at room temperature, respectively. At present, the issue of improving the toughness of high-strength light alloys is one of the hot areas of research. In fact, improving the plasticity and toughness of high-strength light alloys by grain refinement, developing new structures (such as long period stacking ordered structure, or LPSO structure), interface optimization, and texture design are the research focuses of several countries. The development of high-strength and high-toughness flame resistance magnesium alloys and their application in the field of aerospace and automotive light weight are the future trends. The improvement of corrosion resistance of high-strength and high-toughness light alloys is also one of the important subjects.

In addition to their use as structural materials, magnesium alloys may be employed as biodegradable biomedical magnesium alloys and hydrogen storage materials in the future. Biodegradable magnesium alloys have gained significant attention in recent years because they do not cause any adverse effects typically associated with foreign objects staying in the body for a long time after the implantation of inert medical metal materials such as stainless steel and titanium alloy. The development of biomedical magnesium alloys requires regulation of the main composition and microstructure of the alloys. The comprehensive performance of the alloy depends on good mechanical properties, corrosion resistance, and safe biological degradation, a “three-in-one” requirement, in order to meet the needs of clinical application. The focus of research and development of biomedical magnesium alloys is mainly to control the composition and microstructure of alloys so that they exhibit good comprehensive properties of mechanics, corrosion resistance, safe degradation, and biocompatibility in order to meet the needs of clinical applications.

Since 2011, the major countries or regions and institutions that have published patents in the focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys" are given in Table 2.2.5 and Table 2.2.6. Collaboration networks between the major countries or regions and institutions are shown in Figure 2.2.5 and Figure 2.2.6. Among them, China ranks the first with 225 published patents, proportion of published patents of 78.95%, total citation as 2479, proportion of citations of 86.8%, and the average citation of 11.02. Japan ranks the second and in this case, the number of published patents was 29, proportion of published patents was 10.18%. Additionally, the total citation, proportion of citations, and the average citation are 178, 6.23%, and 6.14, respectively. The USA ranks the third and the statistics show that the number of published patents, proportion of published patents, the total citation, proportion of citations, and the average citation are 14, 4.91%, 122, 4.27%, and 8.71, respectively. Among the institutions producing core patents, there are seven in China and three in Japan. From the above data, it is evident that the research output from China in this research field occupies an absolute advantage. Nevertheless, further investigations are crucial for progress in this specific research direction.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	225	78.95%	2479	86.80%	11.02
2	Japan	29	10.18%	178	6.23%	6.14
3	USA	14	4.91%	122	4.27%	8.71
4	Korea	6	2.11%	19	0.67%	3.17
5	Germany	3	1.05%	12	0.42%	4.00
6	France	3	1.05%	4	0.14%	1.33
7	Canada	2	0.70%	14	0.49%	7.00
8	Austria	1	0.35%	4	0.14%	4.00
9	Australia	1	0.35%	14	0.49%	14.00
10	Belgium	1	0.35%	9	0.32%	9.00

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Preparation and applications of aluminum, magnesium, and titanium light metal alloys"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	OBE Steel Ltd.	9	3.16%	44	1.54%	4.89
2	Furukawa Unic Corp	8	2.81%	57	2.00%	7.13
3	Beijing Non-Ferrous Metal Inst	7	2.46%	117	4.10%	16.71
4	China Aluminium Corp	6	2.11%	88	3.08%	14.67
5	Univ Beijing Sci & Technol	6	2.11%	47	1.65%	7.83
6	Cent South Univ	6	2.11%	61	2.14%	10.17
7	Alcoa	5	1.75%	33	1.16%	6.60
8	Anhui Xinyi Cable Co., Ltd.	5	1.75%	109	3.82%	21.80
9	UACJ Corp	5	1.75%	25	0.88%	5.00
10	Beijing Univ Technol	5	1.75%	59	2.07%	11.80

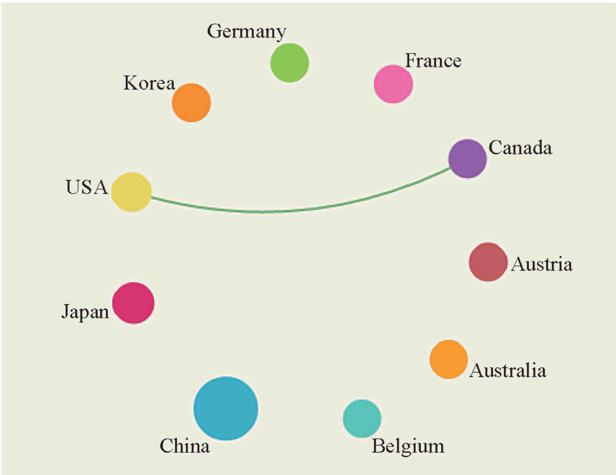

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus “Preparation and applications of aluminum, magnesium, and titanium light metal alloys”

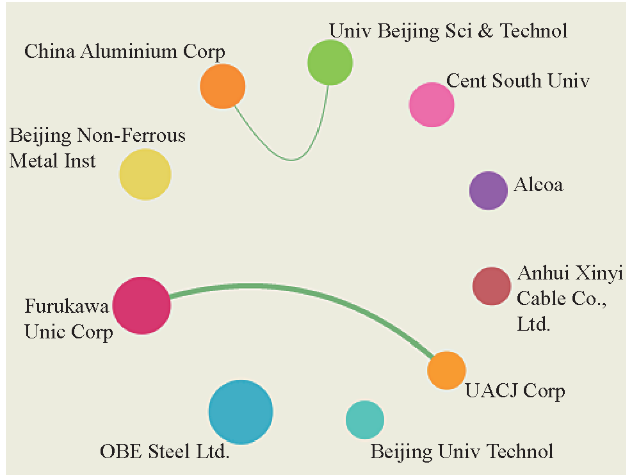

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus “Preparation and applications of aluminum, magnesium, and titanium light metal alloys”

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