III. Chemical, Metallurgical, and Materials Engineering

1 Engineering research fronts

1.1 Trends in top 10 engineering research fronts

The top 10 engineering research fronts determined by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Tables 1.1.1 and 1.1.2. The topics of "smart nanomedicine for cancer therapy," "preparation of novel high-performance porous biomaterials for bone repair," "development and application of next-generation advanced electronic components based on two-dimensional materials," "efficient and robust synthesis of solar fuels," and "non-aqueous potassium-ion batteries with high energy density" are based on core papers provided by *Clarivate*. The other five are recommended by experts or were selected by analyzing data from the *Web of Science*. Basic research on energy, especially pertaining to "efficient and robust synthesis of solar fuels," remains highly topical, and the number of core papers covering this topic has exhibited a general trend of increase. Furthermore, basic research on lithium batteries/capacitors and industrial technologies employing these devices have attracted significant attention.

(1) Smart nanomedicine for cancer therapy

Cancer is among the diseases with the highest mortality rates. Traditional clinical treatments for cancers include chemotherapy, radiotherapy, immunotherapy, and gene therapy. To improve the clinical performance of these therapies while minimizing adverse side effects, nanomedicines—new theranostic agents based on nanotechnology—have been gradually applied in the precise diagnosis and treatment of cancers. Smart nanomedicines have been rationally designed and developed using different biocompatible materials, such as proteins, lipids, polymers, and organic/inorganic nanomaterials with multiple biological functions. Smart nanomedicines can prospectively exhibit simultaneous responses to exogenous stimuli (e.g., light, temperature, ultrasound, magnetic field) and the stimuli in the microenvironment of tumors (pH, reductants, enzymes, reactive oxygen species, and ATP). These responses improve

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Smart nanomedicine for cancer therapy	190	27 890	146.79	2015.7
2	High-energy-density and fast-charging battery–capacitor hybrid energy storage systems	177	27 040	152.77	2016.0
3	Metallurgy and materials processes in high magnetic fields and fabrication of functional materials	139	5 431	39.07	2015.8
4	Preparation of novel high-performance porous biomaterials for bone repair	161	13 121	81.50	2015.8
5	Development and application of next-generation advanced electronic components based on two-dimensional materials	86	15 572	181.07	2015.9
6	Efficient and robust synthesis of solar fuels	77	6 893	89.52	2017.6
7	Non-aqueous potassium-ion batteries with high energy density	52	8 710	167.50	2017.0
8	Ceramic materials for the radome of hypersonic missiles	94	4 140	44.04	2015.7
9	Quantum materials and devices with artificial structures	167	12 065	72.25	2015.5
10	Welding fluxes geared toward high-heat-input applications	115	2 954	25.69	2015.6

Table 1.1.2 Annual number of core papers for the top 10 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Smart nanomedicine for cancer therapy	37	51	51	29	20	2
2	High-energy-density and fast-charging battery–capacitor hybrid energy storage systems	31	48	31	28	31	8
3	Metallurgy and materials processes in high magnetic fields and fabrication of functional materials	34	33	29	24	13	6
4	Preparation of novel high-performance porous biomaterials for bone repair	32	43	30	34	20	2
5	Development and application of next-generation advanced electronic components based on two-dimensional materials	21	15	21	15	10	4
6	Efficient and robust synthesis of solar fuels	0	4	7	21	26	19
7	Non-aqueous potassium-ion batteries with high energy density	1	5	5	24	16	1
8	Ceramic materials for the radome of hypersonic missiles	21	23	22	20	6	2
9	Quantum materials and devices with artificial structures	44	50	33	23	15	2
10	Welding fluxes geared toward high-heat-input applications	23	35	30	21	6	0

the specificity, controllability, and intelligence of nanoparticles for tumor-specific imaging, targeted drug delivery, and precise cancer treatment. Currently, the primary research in this field has been aimed at achieving the following objectives: developing new biocompatible nanomaterials or self-assembly of materials for nanomedicines, stimuli-responsive intelligent nanomedicines for specific cancers and controllable drug release, smart nanoprobes for intelligent tumor imaging and cancer diagnosis, new strategies for developing cancer theranostics for smart nanomedicines, and exploring systemic metabolism and toxicity of smart nanomedicines.

(2) High-energy-density and fast-charging battery–capacitor hybrid energy storage systems

The lithium-ion capacitor (LIC) is a representative high-energy-density and fast-charging battery–capacitor hybrid energy storage system. The energy storage excellent performance of the LIC has both of lithium-ion batteries (LIBs) and a supercapacitor. As a novel energy storage device, the LIC combines the high energy density of LIBs with the high power density and long cycle life of a supercapacitor. The type and structure of the electrode materials, cathode and anode matching, and the potential window of the LIC influence its energy density, power density, and cycle life. At present, most cathode materials for LICs are activated carbon materials with the characteristics of electric double-layer energy storage. Meanwhile, the anode materials are mostly carbon-based with the function of lithium-ion deintercalation. However, the capacity and potential of the carbon materials limit the energy density of devices employing carbon-based electrodes. The use of transition metal oxides, pre-lithiation of the anode materials, and the use of organic electrolytes can render the energy density of LICs comparable to that of LIBs; however, the cycle life and power density of the LIC system must be further improved to be comparable to that of supercapacitors. Therefore, designing and developing new types of high-energy-density electrode materials, tailoring the surface/interface structure of electrode materials, optimizing the process for matching the cathode and anode materials, and achieving miniaturized, flexible, and transparent devices are important research directions for the future development of high-performance LICs.

(3) Metallurgy and materials processes in high magnetic fields and fabrication of functional materials

Improving the service performance of metallic materials and imparting new functions to materials are the major requirements for sustainable development and are also the main challenges in the fields of metallurgy and materials science. A high magnetic field (exceeding 2 T) is usually difficult to achieve with permanent magnets and ordinary electromagnets; it renders a variety of exceptional properties in terms of force, heat, and energy. The efficient coordination of these effects offers significant potential for the design and fabrication of functional metallic materials, and provides a new approach for innovation in metallurgy and material preparation. Multidisciplinary research into metallurgy and materials processes in high magnetic fields is currently trending toward the following objectives: research on the experimental equipment for material preparation and performance testing, measurement of the physical properties of high-temperature metal melts, theoretical research on alloy solidification, development of metallurgical technology, and the design of new metal-based functional materials. It is exceedingly crucial to clarify the effects of synergism and competitive mechanisms involving various phenomena in high magnetic fields on metallurgical and material processes.

(4) Preparation of novel high-performance porous biomaterials for bone repair

With rapid economic development and the aging global population, the number of cases of bone trauma has witnessed a significant increase. Therefore, regenerative medicine is faced with a major challenge; the development of novel bone repair biomaterials is driven by rapidly increasing clinical needs. Bone repair materials with porous structures are required to facilitate the ingrowth of blood vessels, which is critical for bone tissue repair. Scaffolds prepared by 3D printing technology can be used to construct complex shapes matching the bone defect. Furthermore, accurate control of the internal pore structure can be achieved to meet clinical needs. 3D-printed porous scaffolds are usually limited to a single material. Current research is trending toward the development of composites of different types of materials that afford control of the desired scaffold parameters—pore size and type, degradation rate, and mechanical strength—to achieve the most effective bone repair. In addition, constructing fine structures such as nerve and blood vessel networks to reproduce the complex and diverse functions of bone tissue is another goal in the 3D printing of porous bone repair scaffolds. And recent years have witnessed significant progress in the development of bone repair materials, where new bone biomaterials have been designed based on the studies of the interaction of cell materials at the cellular and molecular levels. These studies have led to the development of new technologies for the fabrication of novel bone repair materials with “active repair function” and “tissue microenvironment responsive characteristics” by the accurate control of the chemical composition and nano–micro structure.

(5) Development and application of next-generation advanced electronic components based on two-dimensional materials

Next-generation electronic devices are crucial for developing advanced electronic and photonic integrated circuit technology and realizing miniaturization and integration of high-performance communication and Lidar and electronic warfare systems. Two-dimensional advanced electronic devices afford higher speed, efficiency, and integration, as well as a lower power cost, which should drive a wave of electronic innovation in the near future. The United States and Europe have already focused on two-dimensional advanced electronic devices. Since 2017, particularly the Defense Advanced Research Projects Agency (DARPA) of United States has directed their focus toward advanced devices and materials through the Electronics Resurgence Initiative to attain a technological edge over the rest of the world. Current technology in China is competitively comparable to cutting-edge international developments. Facing unprecedented development opportunities, China also needs to strengthen basic research and development (R&D) and engineering, provide deep research on the preparation and technical problems related to key materials, and establish an independent innovation system. The key challenges are as follows: wafer-scale growth of high-quality single-crystal two-dimensional materials, including graphene, two-dimensional transition metal dichalcogenides, two-dimensional ferromagnetic materials; large-scale nondestructive transfer and hetero-structure integration technology; mechanism of multi-physical-field coupling for high-performance control and manipulation of electronic devices.

(6) Efficient and robust synthesis of solar fuels

Solar energy is a clean, abundant, and renewable power source with tremendous potential. Harnessing solar energy to produce fuels that can be used by human beings is one of the effective ways to solve the global energy crisis and environmental problems. Inspired by natural photosynthesis, solar fuel refers to the use of renewable energy, specifically solar energy, to convert CO_2 and H_2O into chemical fuels (e.g., H_2, CH_3OH). This can be realized in two general ways: One is to use solar energy to decompose H_2O to produce H_2 and O_2 through photo(electro)catalysis and combine H_2 and CO_2 to produce CH_3OH; the other is the direct reduction of CO_2 to CH_3OH by photo(electro)catalysis. This process can achieve zero carbon emissions and is also the main pathway to achieve low-carbon energy. Considering the non-renewable nature of fossil fuels and the increasing demand for energy, the realization of solar fuel is bound to become an important part of the energy structure in the future. Two key catalytic approaches are employed in the process of solar fuel synthesis; the first is utilizing efficient, inexpensive, and stable catalysts for water decomposition/CO_2 reduction by photo(electro) catalysis, with an energy conversion efficiency exceeding 80%, and the other is using inexpensive and highly selective catalysts for the hydrogenation of carbon dioxide to methanol. To improve the conversion efficiency of water splitting into hydrogen/CO_2 reduction, the selectivity and stability of the catalysts and coupling of the two key catalytic technologies are the main research directions in this field.

(7) Non-aqueous potassium-ion batteries with high energy density

Potassium is one of the most abundant elements in the earth's crust and is widely distributed. Its physical and chemical properties are similar to those of lithium, which makes potassium-ion batteries a useful supplement to LIBs. Similar to the working principle of LIBs, charge and discharge processes in potassium-ion batteries are realized by the reversible intercalation and desorption of potassium ions between the positive and negative electrodes. The radius of the potassium ion is larger than that of the lithium ion, while its migration speed is lower in the bulk phase of the material. This leads to a deficiency in the electrochemical performance of the potassium-ion battery. Therefore, the development of anode and cathode materials with stable structures that can undergo reversible insertion and deinsertion has become a key scientific and technological problem to be addressed. At present, the development of cathode materials has mainly focused on Prussian blue, combined with studies of layered transition metal oxide cathodes with high theoretical specific capacity and polyanion cathode materials with high voltage and stability. The primary anode materials are the intercalation/deintercalation and alloy-type anode materials. Although they have certain defects, improved electrochemical performance of modified electrodes can be achieved by element doping, surface coating, and nano-sizing. Research on electrolytes has been mainly aimed at matching the electrolyte and electrode materials. With the advancement of research, potassium-ion batteries are expected to become beneficial complements to LIBs for use in low-speed electric vehicles and large-scale energy storage.

(8) Ceramic materials for the radome of hypersonic missiles

Advanced high-temperature thermoresistant ceramic materials with unique properties are generally used in extreme environments, such as those encountered in prolonged supersonic flight, re-entry flight, crossover flight in the aerosphere, and rocket propulsion. The development of advanced radome materials is one of the key objectives for achieving advanced hypersonic missiles. With the escalating flying speeds of missiles, radome ceramic materials must withstand increasingly harsh working environments. In addition to the various static and dynamic loads, ceramic materials also need to withstand the ablation and corrosion induced by high-temperature, high-pressure, and high-speed airflows. Consequently, ceramic materials for radomes must exhibit excellent mechanical and dielectric properties, resistance to ablation, oxidation, and thermal shock, and an appreciable molding processability to ensure a high transmission power and low aiming error. At present, the advancement of several national key projects is mainly hampered by the lack of advancement in heat-resistant ceramics and their composites. This constraint arises from the insufficient comprehension of the fundamental issues involved in key ceramic processing technologies. The lack of advancement is also attributed to the restricted development of raw materials, such as high-purity ultra-fine ceramic powders/precursors, and major equipment for these processes. Ceramic materials undergo long-term thermo-mechanical coupling ablation; therefore, future efforts should be focused on developing new ceramic fibers and related composites with higher ablation resistance and excellent wave transparency, geared toward achieving improved high-temperature dielectric stability. For large-sized, thin-walled, special-shaped components, it is necessary to develop efficient forming techniques for near-net-size materials. Moreover, dense wave-transmitting ceramic coatings functional at higher temperatures are essential for the porous wave-transparent structural components of radomes.

(9) Quantum materials and devices with artificial structures

Artificially structured quantum materials and devices are novel kinds of semiconductor materials and devices designed and manufactured on the nanoscale via various physical or chemical means. The intriguing properties of these materials mainly originate from the special structures rather than the intrinsic characteristics of the materials. At present, studies on artificial structural quantum materials and devices have focused on the atomic-scale manipulation of defects in two- dimentional materials, design of artificial multiple quantum wells, and periodic structures of superlattices in semiconductor heterostructures. By combining first-principles calculations with micro-machining technology, artificial structural quantum devices with novel functions have been developed by controllable defect doping, and growth of artificially designed structures on the atomic, molecular, or nano scale. The key research targets for developing artificial structural quantum materials and devices are as follows: 1) determining how to precisely and arbitrarily control the thickness of quantum wells/barriers and their multiple stacks; 2) deepening the understanding of the mechanism of interaction between photons, phonons, and electrons in semiconductor quantum dot structures; and 3) comprehending the inherent laws of electron transport, optical transitions, and quantum energy states. The strategic requirements are geared toward further integrating and developing new artificial structural quantum devices, such as highly sensitive mid-infrared detectors, quantum cascade lasers, and superluminescent diodes, by combining high-precision artificial semiconductor microstructures and atomic pattern processing technology.

(10) Welding fluxes geared toward high-heat-input applications

Thick-plate products, such as steel for shipbuilding and offshore engineering, steel for pressure vessels, and steel for hydropower and nuclear power, are of considerable technological importance with high added value. These materials are the "heavy implements of a large country," and having an independent supply and using these materials to meet extreme needs reflect the comprehensive strength of a nation's industrial development strategy and safety. The welding efficiency of these materials has become a bottleneck, restricting the construction of thick-plate products. The manufacture of thick-plate products has been enabled by the wide application of large heat input welding, which affords high efficiency and low cost. From existing research, oxide metallurgy technology is a key point for large heat input welding for thick plates. Domestic R&D for the enhancement of the features of high-grade welding consumables must be improved. The core challenge for obtaining welding consumables from high-strength thick steel plates using a large heat input and high-grade welding materials is to achieve a deeper understanding of the metallurgical welding process, such as flux/slag decomposition, the oxygen gaining mechanism, and alloying element transition of the welds. The welding pool reaction thermodynamics and dynamics model should take into account the evolution process of welding slag structure, alloy element transition, inclusion dissolution and precipitation, which will lead to control over the microstructure of weld metal. This essential regulation is of great significance to consolidate the oxide metallurgy foundation of thick plate large heat input welding and have high performance materials.

1.2 Interpretations for three key engineering research fronts

1.2.1 Smart nanomedicine for cancer therapy

Cancer is a serious threat to human health, with high morbidity and mortality rates. To date, various therapeutic methods, including radiotherapy, chemotherapy, immunotherapy, photodynamic therapy, and gene therapy have been widely used in clinical research and cancer therapy. Cancer therapy has entered the era of precision targeted therapy, with the emergence of smart nanomedicine as a strategy for cancer diagnosis and/or treatment. Smart nanomedicines, as an offshoot of nanoscience and nanotechnology, are geared toward circumventing the various adverse side effects of traditional therapeutics associated with drug delivery, drug enrichment, and systemic toxicity. Smart medicines are also sensitive to exogenous or endogenous stimuli and afford the targeted release and enrichment of sensors or drugs at tumor sites to enhance the biological effects of these agents for cancer diagnosis and cancer treatment.

The following are the main research frontiers for smart nanomedicine: 1) improving the therapeutic effect of traditional chemotherapeutics with the assistance of nanotechnology. Under this objective, various biocompatible materials (e.g., nucleic acids, proteins, lipids) have been designed and developed for producing nanomedicines through chemical conjugation, physical packaging, or supermolecular self-assembly of small-molecule drugs or macromolecule drugs (e.g., nucleic acid drugs, protein drugs, antibodies). Such materials can enhance the stability of drugs and reduce their systemic toxicity. For example, the U.S. Food and Drug Administration-approved albumin-paclitaxel conjugate nano-drug, Abraxane®, is clinically used in the treatment of non-small cell lung cancer and other malignant tumors, affording a significant decrease in the toxicity of paclitaxel to normal organs during cancer therapy. The nanomedicine Doxil® with PEGylated liposomes greatly improved the therapeutic effect of the loaded doxorubicin. 2) Developing specific smart nanomedicines for cancer therapy and their controllable release. Antibody-drug conjugates (ADCs), also known as intelligent biological bombs, exhibit highly active targeting ability for cancers. In January 2020, the National Medical Products Administration of China approved the target nanomedicine Kadcyla® for HER2 positive breast cancer patients, thereby achieving a 50% reduction in recurrence and all-cause mortality in comparison with the use of the trastuzumab HER2 monoclonal antibody. By further using exogenous triggers (e.g., light, temperature, ultrasonic, magnetic field) and endogenous environmental triggers (e.g., pH, Red/Ox, enzymes, ATP), the entrapment of smart nanomedicines in nanomaterials can be maintained during circulation. Meanwhile, drug release can be triggered under certain endogenous or exogenous conditions at tumor sites and the maximum concentration for optimal therapy can be rapidly achieved, resulting in reduced systemic toxicity. 3) Developing smart nanoprobes for tumor imaging and cancer diagnosis, with focus on tumor-specific targeting and multiple modes of precise cancer diagnosis. Numerous specific targeting moieties, including nucleic acid aptamers, antibodies, peptides, and specific small donor molecules, have been conjugated to nanomaterials to develop high-contrast fluorescent nanoprobes, Raman nanoprobes, radionuclide-labeled nanoparticles, and quantum dots to achieve direct tumor diagnosis and surgical navigation. 4) Developing new strategies for synthesizing nanomedicines and theranostics for cancer therapy. Through precise rational design, nanomedicines combined with imaging agents and drugs have been optimized to achieve precise, image-guided tumor treatment. Emerging strategies for cancer therapeutics include targeting nanorobots, *in-vivo* self-assembled nanostructures, and protein nanoreactors for cancer theranostics. 5) Avoiding systemic metabolism and toxicity of nanomedicines. The blood circulation, enrichment, tumor cell penetration, and biological metabolism of nanomedicines with different sizes, morphologies, and surface properties differ from those of traditional drugs. Detailed evaluation of the health safety, therapeutic risk, and toxicological mechanism of nanomedicines will be beneficial for achieving safe clinical cancer therapy.

Among 190 core papers, 67 review papers have been published thus far. The paper titled “Cancer nanomedicine: Progress, challenges and opportunities” published by Harvard Medical School in 2017 received more than 1500 citations. By reviewing core papers focusing on the concept of “smart nanomedicine for cancer therapy” published since 2014, the main countries and institutions involved in this research field are compiled in Tables 1.2.1 and 1.2.2, respectively. The collaboration between major countries and institutions is shown in Figures 1.2.1 and 1.2.2, respectively, where China, the United States, and South Korea are the top three countries for publication in this field. Among the institutions with the highest output of papers in this field, the Chinese Academy of Sciences ranked No. 1. As shown in Figure 1.2.1, China and the United States boast the greatest number of collaborations, and the collaboration networks between France and Italy, the United States and Singapore are also well developed. Figure 1.2.2 demonstrates that the Chinese Academy of Sciences along with the University of Chinese Academy of Sciences and the National Center for Nanoscience and Technology of China are the institutions with the most active collaborations. According to Table 1.2.3, the core papers are most cited by the researchers from China, the United States, and India in a descending order. The top two institutions with the largest number of citing papers are the Chinese Academy of Sciences and the University of Chinese Academy of Sciences (Table 1.2.4).

1.2.2 High-energy-density and fast-charging battery–capacitor hybrid energy storage systems

With the gradual depletion of fossil energy in recent years, the alteration of the energy structure and advancement in the development and large-scale use of new energy technologies have been incorporated into the medium- and long-term development strategies of countries globally. The rapid development of new energy vehicles and smart electronic devices requires energy storage devices capable of fast charging, with high energy density, high power density, and long life. Therefore, there is an urgent need to improve the energy density and power density of energy storage systems to achieve longevity.

Electrochemical energy storage is one of the most effective methods of storing electrical energy, owing to its flexibility, high energy conversion efficiency, and easy maintenance. Thus far, LIBs have been the most successfully developed

Table 1.2.1 Countries with the greatest output of core papers on “smart nanomedicine for cancer therapy”

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	102	53.68%	12 767	125.17	2015.9
2	USA	66	34.74%	12 137	183.89	2015.6
3	South Korea	14	7.37%	1 977	141.21	2015.2
4	Singapore	9	4.74%	909	101.00	2015.2
5	Italy	7	3.68%	1 068	152.57	2015.1
6	Spain	6	3.16%	703	117.17	2015.8
7	India	6	3.16%	570	95.00	2016.2
8	France	5	2.63%	852	170.40	2015.0
9	Portugal	5	2.63%	566	113.20	2016.2
10	Canada	5	2.63%	452	90.40	2015.8

Table 1.2.2 Institutions with the greatest output of core papers on “smart nanomedicine for cancer therapy”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	39	20.53%	4 923	126.23	2015.8
2	University of Chinese Academy of Sciences	15	7.89%	2 284	152.27	2016.0
3	Soochow University	14	7.37%	1 520	108.57	2015.9
4	Harvard University	12	6.32%	4 310	359.17	2016.0
5	National Center for Nanoscience and Technology of China	7	3.68%	716	102.29	2015.9
6	Xiamen University	6	3.16%	1 056	176.00	2016.8
7	Massachusetts Institute of Technology	5	2.63%	1 916	383.20	2014.4
8	National Institute of Biomedical Imaging & Bioengineering, National Institutes of Health	5	2.63%	878	175.60	2016.4
9	Seoul National University	5	2.63%	774	154.80	2014.6
10	University of North Carolina at Chapel Hill	5	2.63%	577	115.40	2015.0

electrochemical energy storage technology. However, the limited kinetics of the chemical reactions of the constituents and the reaction mechanisms of LIBs make it difficult to achieve high power density and long life. In contrast, while supercapacitors boast of these characteristics, they cannot provide high capacity and energy density. The LIC is a special energy storage system that combines LIB-type electrodes and capacitor-type electrodes. Thus, LICs have a high energy density close to that of LIBs and the high-power characteristics of supercapacitors.

Recent years have witnessed a rapid development in battery–capacitor energy storage systems based on LIBs and supercapacitors. Research on electrochemical energy storage materials and devices is an interdisciplinary field involving

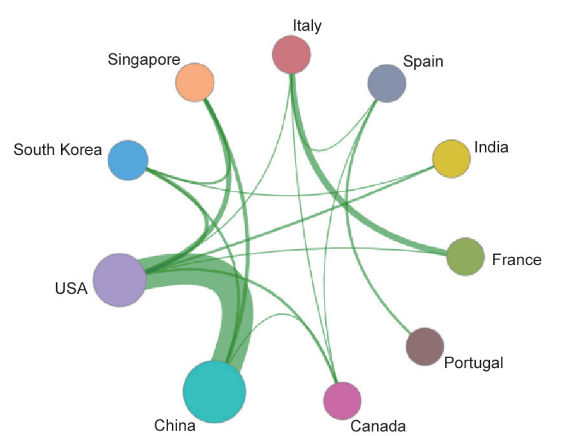

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “smart nanomedicine for cancer therapy”

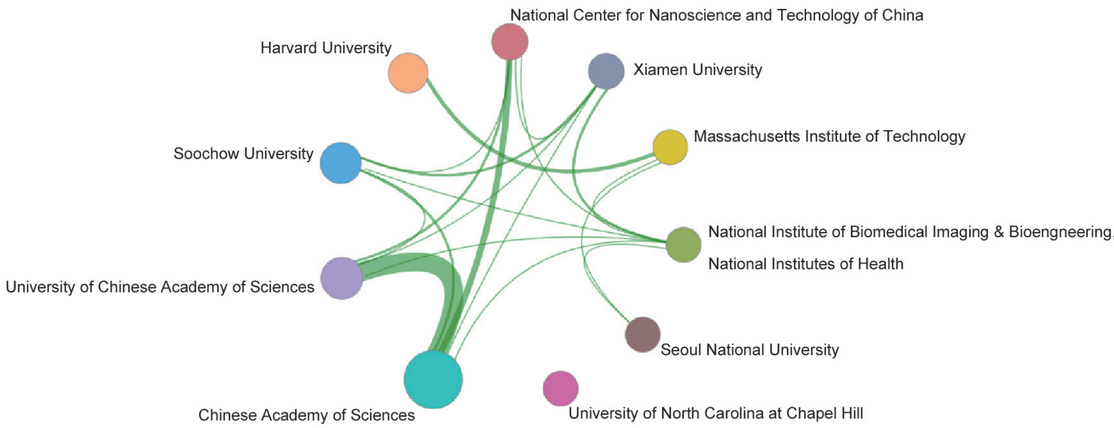

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “smart nanomedicine for cancer therapy”

Table 1.2.3 Countries with the greatest output of citing papers on “smart nanomedicine for cancer therapy”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	10 396	50.47%	2018.1
2	USA	3 673	17.83%	2017.8
3	India	1 146	5.56%	2018.1
4	South Korea	898	4.36%	2018.0
5	Germany	726	3.52%	2018.0
6	Spain	680	3.30%	2017.9
7	Iran	679	3.30%	2018.3
8	Italy	663	3.22%	2017.8
9	UK	619	3.01%	2018.0
10	France	567	2.75%	2017.8

Table 1.2.4 Institutions with the greatest output of citing papers on “smart nanomedicine for cancer therapy”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	1 792	30.43%	2018.0
2	University of Chinese Academy of Sciences	716	12.16%	2018.1
3	Soochow University	483	8.20%	2017.7
4	Shanghai Jiao Tong University	440	7.47%	2018.2
5	Zhejiang University	386	6.56%	2018.3
6	Sichuan University	368	6.25%	2018.0
7	Jilin University	364	6.18%	2018.1
8	Fudan University	364	6.18%	2018.1
9	University of Science and Technology of China	340	5.77%	2018.4
10	Harvard University	335	5.69%	2017.8

materials science, physics, chemistry, and metallurgy, and is wide-ranging and relatively complex. The following are the principal research hotspots in the field: 1) the development of new electrode materials to improve the energy density of these systems. Research on new battery-type electrode materials has mainly focused on high-capacity metal oxide materials, such as Li–Ni–Mn–O and Nb_2O_5. Meanwhile, pseudocapacitive materials are often used for capacitor-type electrode materials instead of carbon materials such as MXenes and MoO_3. Surprisingly, with some new electrode materials, the energy density and power density of LICs can reach 92.3 Wh/kg and 1100 W/kg, respectively. 2) Developing nanostructured electrode materials. Designing, tailoring, and preparing nanomaterials with different morphologies and structures that can be modified by applying an electromagnetic field, coating, element doping, or surface/interface design can afford enhanced kinetic characteristics of electrochemical reactions, and higher specific surface area and conductivity of electrode materials. The improved characteristics result in the enhanced power density and cycle performance of LICs. Moreover, the high wettability and ion/electron transport properties of three-dimensional integrated electrodes offer distinct advantages for improving the performance of LICs. 3) The development of new electrolytes to improve the electrochemical performance and safety of LICs. The primary characteristics of electrolytes to be considered are their voltage window ranges, ionic conductivities, thermal stabilities, and compatibility with electrode materials. In 2015, *Science* reported a "water-in-salt" electrolyte; the unique electrolyte displayed good thermal stability and a high voltage resistance in battery–capacitor systems. Based on the high power density, this electrolyte effectively improves the energy density of water-based battery-capacitors. 4) Diversification and functionalization of battery–capacitors. High energy density, high power density, and long-life energy storage devices will have broad application prospects in smart/wireless electronic devices and optoelectronic devices. Therefore, the future will witness a great demand for flexible, foldable, and even transparent battery–capacitor devices. In addition, high-capacity sodium ion capacitors with fast electrochemical reaction kinetics will have broad prospects.

The main countries involved in research and the institutions publishing core papers covering the concept of "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems" since 2014 are listed in Tables 1.2.5 and 1.2.6, respectively; the collaboration between major countries and institutions is outlined in Figures 1.2.3 and 1.2.4. China, the United States, and South Korea are the top three countries, while the Chinese Academy of Sciences ranked No. 1 with the highest output of core papers. As shown in Figure 1.2.3, China and the United States boast the greatest number of collaborations. The core papers are most cited by the researchers from China, the United States, and South Korea in a descending order (Table 1.2.7). The Chinese Academy of Sciences, together with the University of Chinese Academy of Sciences, are the institutions with the greatest output of citing papers (Table 1.2.8). Research from Gleb Yushin at the Georgia Institute of Technology and Yi Cui of Stanford University is highly advanced. The 2016 review titled "Electrochemical capacitors: Mechanism, materials, systems, characterization and applications" by Yongyao Xia of Fudan University received more than 1300 citations in the last five years.

Table 1.2.5 Countries with the greatest output of core papers on "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems"

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	95	53.67%	13 859	145.88	2016.4
2	USA	58	32.77%	11 617	200.29	2016.0
3	South Korea	15	8.47%	2 212	147.47	2015.6
4	Germany	11	6.21%	1 821	165.55	2016.4
5	Canada	11	6.21%	1 461	132.82	2016.5
6	Japan	9	5.08%	912	101.33	2015.0
7	Singapore	7	3.95%	1 468	209.71	2015.0
8	Australia	7	3.95%	957	136.71	2015.9
9	UK	5	2.82%	703	140.60	2016.8
10	France	5	2.82%	587	117.40	2014.8

Table 1.2.6 Institutions with the greatest output of core papers on "high-energy-density and fast-charging battery–capacitor hybrid energy storage systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Chinese Academy of Sciences	18	10.17%	2 129	118.28	2016.0
2	Fudan University	8	4.52%	1 757	219.62	2017.0
3	Tsinghua University	8	4.52%	908	113.50	2017.6
4	Nanyang Technological University	7	3.95%	1 468	209.71	2015.0
5	Nanjing University	7	3.95%	768	109.71	2015.6
6	Brookhaven National Laboratory	7	3.95%	535	76.43	2015.0
7	Stanford University	6	3.39%	1 375	229.17	2016.0
8	Argonne National Laboratory	6	3.39%	830	138.33	2016.8
9	University of Chinese Academy of Sciences	6	3.39%	769	128.17	2017.7
10	University of Waterloo	5	2.82%	894	178.80	2017.0

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "high-energy-density and fast-charging battery–capacitor hybrid energy storage system"

1.2.3 Metallurgy and materials processes in high magnetic fields and fabrication of functional materials

High-efficiency green metallurgy and material preparation technologies can improve the service performance of structural metallic materials and afford novel functional materials. These materials constitute the major needs of China's high-end equipment manufacturing, aerospace, energy, and other industries, as well as the core of the research in the fields of metallurgy and materials. Magnetic fields, especially high magnetic fields (exceeding 2 T), are difficult to achieve with permanent magnets and ordinary electromagnets. As a non-contact extreme physical field, high magnetic fields can act on matter on the atomic scale. This interaction can result in various enhanced effects, such as Lorentz force, thermoelectric magnetic force (a special

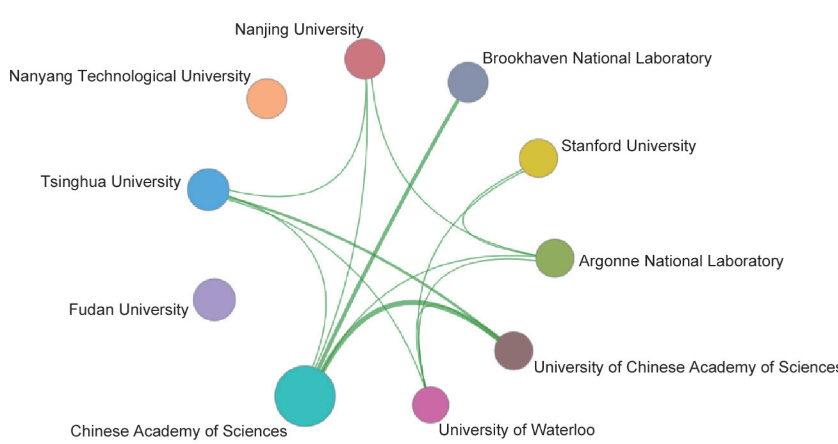

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "high-energy-density and fast-charging battery–capacitor hybrid energy storage system"

Table 1.2.7 Countries with the greatest output of citing papers on “high-energy-density and fast-charging battery–capacitor hybrid energy storage systems”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	12 484	53.07%	2018.3
2	USA	3 670	15.60%	2018.1
3	South Korea	1 584	6.73%	2018.2
4	Germany	1 238	5.26%	2018.1
5	Australia	891	3.79%	2018.3
6	India	818	3.48%	2018.3
7	Japan	707	3.01%	2018.2
8	Canada	592	2.52%	2018.3
9	Singapore	544	2.31%	2017.8
10	UK	534	2.27%	2018.3

Table 1.2.8 Institutions with the greatest output of citing papers on “high-energy-density and fast-charging battery–capacitor hybrid energy storage systems”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	1 687	29.39%	2018.2
2	University of Chinese Academy of Sciences	644	11.22%	2018.3
3	Tsinghua University	588	10.24%	2018.1
4	University of Science and Technology of China	427	7.44%	2018.4
5	Central South University	407	7.09%	2018.0
6	Nankai University	389	6.78%	2018.1
7	Harbin Institute of Technology	328	5.71%	2018.2
8	Nanyang Technological University	322	5.61%	2017.6
9	Huazhong University of Science and Technology	321	5.59%	2018.0
10	Peking University	318	5.54%	2018.3

kind of Lorentz force), magnetic force, magnetic torque, magnetic dipole-dipole interactions, or magnetization energy on materials. These effects provide unique methods for controlling the solidification of metallic materials, which is the key issue in metallurgy and material preparation. Therefore, exploiting these effects offers the possibility of new innovations in metallurgy and material fabrication for achieving novel functional materials.

In recent years, metallurgy and material processes employing high magnetic fields have been regarded as both prospective and strategic research undertakings globally. The Japan Science and Technology Agency has formulated a special research project for the “Development of New Materials under High Magnetic Field Conditions,” and the National High Magnetic Field Laboratory of the United States has carried out a series of studies on high-temperature superconducting materials, alloy materials, and composite materials in high magnetic fields. France, the United Kingdom, Germany, and other countries have also carried out similar studies. Since 2000, independent research teams have been established in numerous universities and institutes in China, mainly focusing on the solidification behavior of metallic materials. After nearly 20 years of accumulation, they have successfully developed a series of special experimental apparatuses that are operational under high-magnetic-field conditions. Furthermore, they achieved considerable experimental and theoretical advancements in terms of the transfer behavior of fluid flow, solute migration, heat transfer, and the effects of these processes on microstructure evolution during the solidification of metallic materials in high magnetic fields.

Prospective studies in this field should address the following: 1) equipment for material preparation and performance testing in a high-magnetic-field environment, where such equipment should be reliable and have comprehensive functions for material preparation, physical property analysis, microstructural analysis, and performance monitoring. 2) Measurement of physical properties of metals at high temperatures in high magnetic fields. The physical properties include the electrical conductivity, viscosity, magnetic susceptibility, diffusion coefficient, contact angle, and phase transition temperature, which are the bases for the quantitative analysis of the various force and energy effects of high magnetic fields. Analyzing these parameters will provide a framework for addressing other major fundamental issues pertaining to high magnetic fields. 3) Theoretical studies on the solidification of alloys in high magnetic fields, including fluid flow behavior, solute diffusion and migration, solid/liquid interface stability, and crystal growth. These theories are the basis for determining the mechanisms by which the magnetic field exerts these effects. Moreover, the design of metallurgy-controlling techniques using a high magnetic field is influenced by these theories. 4) Development of novel high magnetic field-controlled metallurgy technologies. The key points are the application of high magnetic fields to melt treatment, liquid forming, casting, directional solidification, liquid phase sintering, and other traditional metallurgy and material preparation processes for preparing metallic materials in a "non-contact" manner. The objective is to regulate the solidification structure of materials via an effective and green approach. 5) Design and fabrication of novel functional metallic materials. High-intensity magnetic field metallurgy and material preparation technology can aid in developing high-performance functional materials with properties such as magnetostriction, magnetic storage, and permanent magnetism, along with thermoelectric, magnetocaloric, and magneto-optical properties. Materials with special structures such as gradient distribution, anisotropy, and second-phase enhancement can also be obtained.

The main countries and institutions conducting research on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials" are listed in Tables 1.2.9 and 1.2.10, respectively. The collaboration between major countries and institutions is shown in Figures 1.2.5 and 1.2.6. China, the United States, Iran, and Germany are the top four countries with the most publications in this field. Among the institutions with the highest output of papers, Shanghai University is ranked No. 1. As shown in Figure 1.2.5, China and the United States have the greatest number of collaborations, and the collaboration networks between China and Germany, China and France, China and Iran, Iran and Australia, and France and Tunisia are also well developed. Figure 1.2.6 demonstrates that the most active collaboration among institutions involves Shanghai University, Aix-Marseille University, French National Centre for Scientific Research, and the Chinese Academy of Sciences. As shown in Table 1.2.11, the top three countries with the highest output of citing papers are China, the United States, and Germany, while Table 1.2.12 demonstrates that Northeastern University, the Chinese Academy of Sciences, and Babol Noshirvani University of Technology are the top three institutions that employ the core literature as their references.

Table 1.2.9 Countries with the greatest output of core papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Country	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	China	61	43.88%	1 870	30.66	2015.8
2	USA	20	14.39%	799	39.95	2016.1
3	Iran	19	13.67%	1 438	75.68	2017.6
4	Germany	19	13.67%	1 242	65.37	2015.4
5	France	18	12.95%	473	26.28	2014.9
6	Australia	10	7.19%	498	49.80	2016.2
7	Japan	8	5.76%	296	37.00	2015.9
8	India	8	5.76%	247	30.88	2015.9
9	Tunisia	6	4.32%	165	27.50	2014.3
10	Russia	6	4.32%	149	24.83	2016.0

Table 1.2.10 Institutions with the greatest output of core papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Mean year
1	Shanghai University	17	12.23%	382	22.47	2015.5
2	Babol Noshirvani University of Technology	12	8.63%	1 230	102.50	2018.3
3	Northeastern University	10	7.19%	277	27.70	2015.4
4	Chinese Academy of Sciences	8	5.76%	181	22.62	2015.4
5	French National Centre for Scientific Research	7	5.04%	188	26.86	2014.4
6	University of Science and Technology Beijing	4	2.88%	135	33.75	2015.8
7	Dalian University of Technology	4	2.88%	115	28.75	2014.8
8	Aix-Marseille University	4	2.88%	93	23.25	2014.5
9	Xi'an Jiaotong University	3	2.16%	252	84.00	2017.7
10	Public Authority for Applied Education & Training	3	2.16%	222	74.00	2018.0

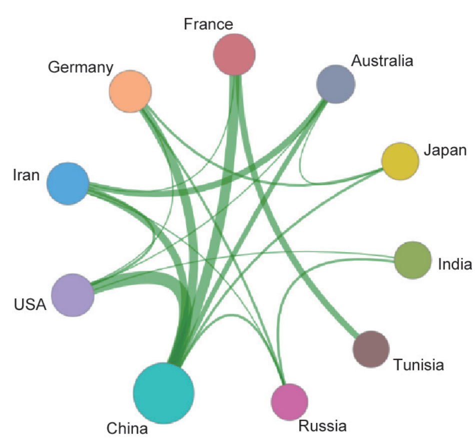

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

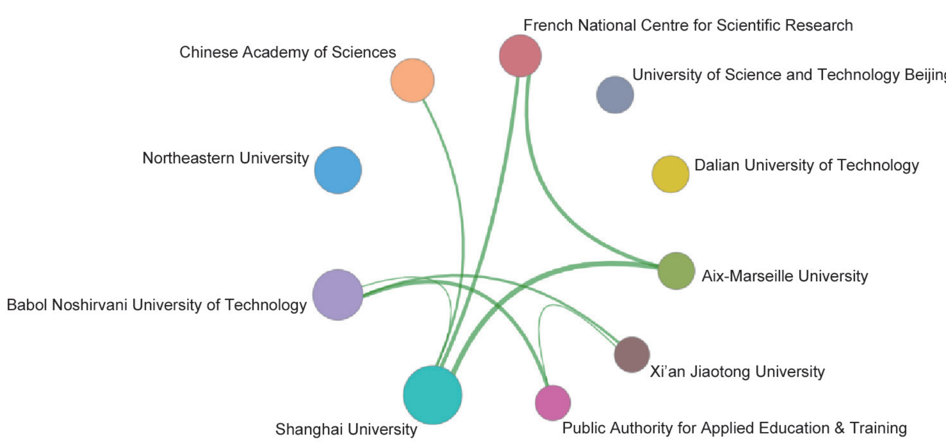

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

Table 1.2.11 Countries with the greatest output of citing papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	1 678	35.01%	2018.1
2	USA	643	13.42%	2018.0
3	Germany	352	7.34%	2017.9
4	Iran	347	7.24%	2018.6
5	France	333	6.95%	2017.7
6	Japan	282	5.88%	2018.0
7	India	259	5.40%	2018.2
8	Russia	257	5.36%	2017.9
9	Saudi Arabia	225	4.69%	2018.4
10	Pakistan	215	4.49%	2018.5

Table 1.2.12 Institutions with the greatest output of citing papers on "metallurgy and materials processes in high magnetic fields and fabrication of functional materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Northeastern University	224	17.23%	2017.8
2	Chinese Academy of Sciences	177	13.62%	2018.0
3	Babol Noshirvani University of Technology	133	10.23%	2018.8
4	Shanghai University	130	10.00%	2017.8
5	Ton Duc Thang University	128	9.85%	2019.1
6	Islamic Azad University	96	7.38%	2018.6
7	Jilin University	90	6.92%	2018.0
8	University of Wollongong	89	6.85%	2018.7
9	University of Science and Technology Beijing	81	6.23%	2018.3
10	Russian Academy of Sciences	76	5.85%	2017.9

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. "All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology" and "precision etching of semiconductors" are based on the patents provided by *Derwent Innovations Index*. The other eight are recommended by experts. Of the ten fronts, four are interdisciplinary of chemical/environmental/energy/materials/metallurgical science and engineering (i.e., "degradation and recycling of waste plastics," "all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology," "multi-scale, multi-dimensional, *in-situ* dynamic analysis technology," and "refined sorting technology and equipment for multiple-composite solid waste"); four fronts are about metallurgy ("manufacturing technology for new-generation shipbuilding steel," "high-temperature titanium alloy system and parts for aviation," "low-cost and high-quality additive forging for key components of major equipment," and "super-bearing steel with high cleanliness and heavy refined structure"); and two of the fronts are about materials research ("precision etching of semiconductors" and "development of smart materials and technology with high adaptability for intelligent manufacturing equipment”). The annual number of core patents falling under “multi-scale, multi-dimensional, *in-situ* dynamic analysis technology” and “low-cost and high-quality additive forging for key components of major equipment” witnessed a rapid increase (Table 2.1.2). Technologies for environmental applications, such as “degradation and recycling of waste plastics” rank as No. 1, and patents falling under “refined sorting technology and equipment for multiple-composite solid waste” have 13.69 citations per patent, which is the highest among all top 10 fronts.

(1) Degradation and recycling of waste plastics

The rapid development of the plastics industry has led to large quantities of waste plastics. The existing treatments for waste plastics by disposal in landfills, incineration, or

Table 2.1.1 Top 10 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Degradation and recycling of waste plastics	627	649	1.04	2017.0
2	All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology	818	3 706	4.53	2016.0
3	Manufacturing technology for new-generation shipbuilding steel	595	2 590	4.35	2015.0
4	Precision etching of semiconductors	546	5 028	9.21	2014.6
5	Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology	954	802	0.84	2018.4
6	High-temperature titanium alloy system and parts for aviation	410	713	1.74	2016.5
7	Low-cost and high-quality additive forging for key components of major equipment	967	4 369	4.52	2017.7
8	Super-bearing steel with high cleanliness and heavy refined structure	656	3 916	5.97	2015.4
9	Development of smart materials and technology with high adaptability for intelligent manufacturing equipment	1 223	6 469	5.29	2016.6
10	Refined sorting technology and equipment for multiple-composite solid waste	807	11 049	13.69	2016.6

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Degradation and recycling of waste plastics	38	47	57	92	199	153
2	All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology	93	90	83	103	144	166
3	Manufacturing technology for new-generation shipbuilding steel	74	60	64	75	78	76
4	Precision etching of semiconductors	82	56	65	60	59	52
5	Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology	5	4	27	108	176	628
6	High-temperature titanium alloy system and parts for aviation	49	54	65	83	73	69
7	Low-cost and high-quality additive forging for key components of major equipment	21	49	76	186	275	348
8	Super-bearing steel with high cleanliness and heavy refined structure	78	100	84	91	57	107
9	Development of smart materials and technology with high adaptability for intelligent manufacturing equipment	89	123	234	233	254	216
10	Refined sorting technology and equipment for multiple-composite solid waste	49	46	101	143	190	189

discarding lead to serious environmental pollution and resource wastage. Tremendous efforts have been expended to degrade and recycle waste plastics. As one approach, low-cost and degradation-controllable biodegradable plastics should be developed, where these plastics can eventually be decomposed by natural microorganisms and re-enter the ecosystem in the form of CO_2 and water. In another approach, technologies have been developed for converting waste plastics into regenerative plastics, energy, or small-molecule chemicals by using machinery, heat, solvents, and other methods. The key points in this approach include developing high-efficiency and high-selectivity catalytic systems, green and mild solvent systems, and efficient product separation techniques. New recyclable plastics comprising recyclable monomers and reversible dynamic bonds have been considered. Future development strategies should focus on application-oriented closed-loop and upgraded recycling technologies to maximize resource utilization and environmental protection. For applications in which the collection of waste plastics is difficult, plastics that biodegrade quickly and harmlessly under the environmental conditions of waste are in high demand. For applications in which waste plastics are easy to collect, efforts should be strengthened to achieve efficient clean recovery and high-value utilization of waste plastics and recyclable plastics with good performance.

(2) All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology

Electrochemical energy storage systems afford the ability to track load changes and offer high response speed, accurate control, and the dual functions of bi-directional regulation and peak shaving and valley filling. Thus, these systems are an important peak-shaving power supply. Solid-state lithium batteries are characterized by high specific energy, safety, and long life. LICs have significant advantages such as high power, a wide operational temperature range, and fast response. By exploiting the innovation of polymer solid-state lithium batteries and lithium capacitors, a novel integrated all-climate electrochemical energy storage system with high energy and high power can be achieved. Current research is mainly focused on: 1) developing solid electrolyte and cobalt-free cathodes; 2) industrial production of key materials for cobalt-free solid-state batteries; 3) preparation engineering technology for solid-state electrodes and solid-state single cells; 4) rapid lithium-ion storage technology; 5) precise and controllable pre-lithium and new ultra-low-temperature compounding techniques; and 6) efficient and intelligent integration and demonstration of dual-source energy storage systems.

(3) Manufacturing technology for new-generation shipbuilding steel

Iron and steel are the most critical structural materials for shipbuilding. The properties of these materials are directly related to the advanced technology, service life, and safety and reliability of ships. For large vessels, the United States initially proposed the development of new-generation high-strength low alloy (HSLA) hull steel. Currently, easily weldable high-strength series, such as HSLA80, HSLA100, HSLA115, and HSLA130 steels, are employed for ship construction. For underwater applications, Russia has developed a structural hull steel for pressure shell with a yield strength of 1175 MPa to be employed in vessels that can dive to depths exceeding 650 m. With the development of large-scale and deep-diving ships, hull structural steel requires high strength, high toughness, and must be easily weldable. Three advanced research areas should be considered: 1) smelting technology of ultra-low-carbon clean steel, 2) new-generation thermo mechanical control process (TMCP) based on ultra-fast cooling technology, and 3) matching welding materials and welding technology for shipbuilding.

(4) Precision etching of semiconductors

Semiconductor materials and technology play a central role in the fields of computers, communications, and electronics, and are also the cornerstones in the development of social informatization. Precision etching is the core technology in the semiconductor industry and the foundation of advanced manufacturing processes. The performance of semiconductor devices is directly influenced by the etching precision. The precision of etching techniques is an important index for evaluating the level of development of the semiconductor industry. Etching is a chemical or physical method that selectively removes material, and current etching processes can be divided into wet and dry etching. The etching quality is evaluated by the direction, selectivity, rate, and uniformity of etching. In the large-scale production of semiconductors, precision etching requires high reliability to ensure appreciable continuity and low defect rates. Wet etching, which affords high selectivity, is generally used for grinding, polishing, cleaning, and removing corrosion from traditional silicon-based semiconductors. Meanwhile, dry etching, with anisotropic features, can be used to construct the fine structure of integrated circuits. With improvements in the semiconductor manufacturing process and the demand for semiconductors with a smaller critical size, etching processes must afford high selectivity, high stability, and anisotropy. Furthermore, there is a rapid development in new third-generation semiconductor materials, such as silicon carbide and gallium nitride. Thus, etching processes must be adapted to the novel characteristics of these new materials to achieve devices that are operational under high-temperature, high-radiation, and high-power conditions. Owing to the requirements for small size, high integration, and new materials for integrated circuits, precision etching can be employed to improve the processing reliability. Precision etching can also afford breakthroughs in resolution through innovative approaches to optimize the working medium for etching, strengthen control of the etching process, and explore new etching principles. Finally, precision etching would definitely contribute to the semiconductor industry and information society.

(5) Multi-scale, multi-dimensional, *in-situ* dynamic analysis technology

Multi-scale (nanometer to centimeter), multi-dimensional (2D, 3D, 4D), *in-situ* dynamic analysis using the synchrotron radiation source at the national large scientific facility in China is an advanced frontier characterization technique with high temporal and spatial resolution. This high-performance technique allows the *in-situ*, dynamic, real-time observation of the formation and evolution of microstructures or defects in novel materials during the preparation process. Microstructural evolution and damage to materials under simulated extreme service environments can also be monitored. Quantitative data on the temporal evolution of the microstructure of materials or related information (such as the chemical composition) can also be acquired. This technology has become a powerful tool for revealing the relationships between material composition, microstructure, processing, and service performance, as the elucidation of these relationships is critical for addressing scientific issues in material research. For example, multi-scale, multi-dimensional, *in-situ* dynamic analysis technology can be employed to study the microstructural evolution and mechanisms of damage in a series of advanced metallic materials used for the key components of major equipment (such as aeroengine blades, lunar rover cantilever beams, and icebreaker propellers) during the preparation and processing steps. Corresponding changes under simulated, complex, extreme service environments (extremely high/low temperature or alternating temperature, corrosion, or the coupling of these factors) can also be monitored, which is critical for developing physical models of the materials and improving the service performance and safety of the key components of those major equipment. Further development of this technology is geared toward: 1) the design and construction of *in-situ* devices for material preparation using coupled external multi-fields, and for evaluating the performance of these materials under extreme service conditions; 2) the development of high spatial/temporal resolution and high-precision synchrotron radiation X-ray methodology, as well as automatic data analysis technology; 3) the development and joint applications of techniques using coupled X-ray methods, such as synchrotron radiation X-ray imaging, diffraction, fluorescence, and scattering.

(6) High-temperature titanium alloy system and parts for aviation

Owing to their excellent properties, especially high specific strength and fatigue resistance, high-temperature titanium alloys are widely used in aerospace applications, such as aero engine room, heat shield, casing, turbine disk, high pressure compressor blade and disk. It is important to develop new alloy components and technologies for synthesizing and processing high-temperature titanium alloys. Such technologies include casting, forging, powder metallurgy, and 3D printing. Ingots prepared by multiple processes exhibit better microstructures and mechanical properties than those prepared using a single process. High-temperature titanium alloys, mainly comprise the α-phase and β-phase, under different strengthening modes and phase transitions, and afford equipment with a service temperature of up to 480 °C; this can be further extended to 550–650 °C with the addition of trace alloying elements. Advanced studies on high-temperature titanium alloys for aviation have focused on: 1) the size, shape, and content of the α-phase, β-phase, enhanced phase, and α_2-phase, to improve the stability of the microstructure of high-temperature titanium alloys;

2) developing joint-preparation technologies for large ingots, while controlling the microstructure of the α-flake structure, α-equiaxial structure, and the transformation matrix of the β structure. This was aimed at achieving higher-temperature applications by exploiting the high plasticity and good thermal stability of these alloys; 3) using the directional solidification technology to prepare columnar or single crystal blade billets of high temperature titanium alloy with excellent properties; 4) using the finite element model to determine the proper size of the α_2-phase and the critical transition point based on the composition of high-temperature titanium alloys to achieve appreciable thermal strength and stability. This approach is crucial for providing theoretical support for developing high-performance, high-temperature titanium alloys for aviation.

(7) Low-cost and high-quality additive forging for key components of major equipment

Heavy forgings are the core components of major equipment and play an indispensable role in national defense security and the national economy. Conventionally, to manufacture a heavy component of up to hundreds of tons, a super-large steel ingot is required. Unfortunately, owing to the size effect of solidification, heavy forgings derived from ingots weighing hundreds of tons always have severe defects, such as macro-segregation and shrinkage. These defects severely deteriorate the quality and performance of the forgings. Consequently, the homogeneous manufacture of heavy forgings has become an urgent issue of global concern. Three-dimensional printing has been used to manufacture large components, such as titanium alloy large integral main bearing structural parts, where the performance of these components may be comparable to that of forgings. However, for iron-based and nickel-based materials, 3D printing has always been limited in terms of economy and reliability compared to traditional forging methods. In recent years, China has played a leading role in the use of metal additive forging to manufacture high-quality heavy forgings. This technology combines the advantages of traditional forging with emerging additive manufacturing, enabling the low-cost and high-quality manufacturing of heavy components for energy and electricity applications. At present, metal additive forging is in the preliminary stages and is used for engineering applications in wind power, hydropower, nuclear power, and other fields. It is noteworthy that the research and application of this technology are in the initial stage. Meanwhile, the key restrictions to the large-scale application of metal additive forging include: 1) lack of prepare methods for base elements with the appropriate size for different alloy systems; 2) lack of efficient techniques for cleaning and activating the surface of the base elements; 3) lack of methods for breaking and decomposing the oxidation film during interface bonding; and 4) underdeveloped additive forging of heavy components for superalloys, titanium alloys, and special stainless steels. The following approaches are recommended for solving the above problems: 1) establishing general technical standards for metal additive forging, determining the evaluation system and application criteria for components manufactured by additive forging, and expanding this technology as the cutting-edge technique for developing heavy component limit manufacturing globally; 2) exploring efficient methods for cleaning and activating the alloy surfaces, developing special surface treatment equipment and intelligent production lines for additive forging, and replacing traditional large steel ingots with high-quality and low-cost additive forging billets; 3) further developing additive forging techniques for large-scale and homogenous material systems for heavy gas turbine disks, nuclear power/hydrogenation pressure vessels, and high-quality mold steels, developing and assessing the sample pieces, and delineating technical specifications.

(8) Super-bearing steel with high cleanliness and heavy refined structure

Bearing steels are recognized as steels with the highest requirements for material quality, known as “the king of steel.” High-end bearings are mainly used in aero-engines, marine equipment, high-speed trains, shield machines, computer numerical control machine tools, and wind power. Service life and reliability are the key elements of bearings. First, new steel materials with high cleanliness, good homogeneity, and adequate microstructures are required to circumvent the early failure of bearings, insufficient strength and toughness, and poor wear resistance problems. Second, comprehensive system standards should be established for bearing steels, such as regulating the oxygen content or Ti content of bearing steel. The third area is developing advanced metallurgical technology for bearing steel, including new refining and continuous casting techniques. This is very important for preventing the problem of large discrete inclusions, especially in the case of large ingots. Field-enhanced refining, continuous casting, solidification, and remelting processes, such as electromagnetic refining, new electromagnetic continuous casting, continuous casting heavy reduction, large ingot solidification with field control, and magnetically controlled electroslag remelting technology, are expected to provide high cleanliness, ultra-fine, high homogenization, and high service performance of bearing steel.

(9) Development of smart materials and technology with high adaptability for intelligent manufacturing equipment

Developing intelligent manufacturing equipment is an important driving force for achieving intelligent manufacturing technology. Intelligent manufacturing integrates advanced manufacturing, digital control, modern sensing, and artificial intelligence, and has functions such as perception, learning, decision-making, and execution. Compared with traditional manufacturing equipment, intelligent manufacturing equipment with high adaptability can be used to realize customized and multi-purpose production. Intelligent manufacturing equipment can actively receive external information and conduct independent analysis and execution to adapt to complex processing environments and procedures during manufacturing with different materials, different material types, or different processes. Thus, a large number and volume of sensors and actuators with multiple functions are required for such equipment. Smart materials respond quickly, and simultaneously possess the functions of sensors and actuators. These features enable miniaturization, diversification of functions, and afford simple structures of intelligent manufacturing equipment, thereby improving the adaptability and reliability of the equipment. Smart materials have a high response speed, generate a strong driving force, and their performance can be tailored to the requirements. They can respond to external stimuli, including temperature and humidity, pH, gas, mechanical force, and light, which endows the structures with intelligence. These features meet the requirements of intelligent manufacturing trends and have received immense attention. Smart materials have been applied in high-sensitivity sensors, flexible robot drives, mechanical vibration control, self-detection and self-repair of damage to structural equipment, equipment working status detection, and other manufacturing fields. Nevertheless, research on smart materials used in intelligent manufacturing equipment is still in its infancy and requires further development. On one hand, it is necessary to develop smart materials with higher response speed, greater driving force and driving stroke, and lower requirements for operation in the working environment. On the other hand, it is essential to combine a variety of smart materials to form smart structures to improve the range of use and work performance from the perspective of engineering design.

(10) Refined sorting technology and equipment for multiple-composite solid waste

Multiple-composite solid wastes (MCSWs) are mainly decommissioned products, including electronic waste, spent batteries, waste organic composite materials, waste textiles, and waste packaging. The distinct characteristics, such as complex phase composition and structure, complex phase-to-phase interface, and dual attributes of being a resource as well as an environmental burden, are significantly different from those of traditional industrial waste and other solid wastes. Consequently, the refined sorting of MCSWs is essential for efficient recycling of its resources. Existing waste separation technologies are generally based on traditional mineral separation and metallurgical principles. These separation techniques combine multidisciplinary theories regarding materials, the environment, machinery, and intelligent control. The major demands of the recycling industry market are promoting refined separation for short-cut resource recycling and material utilization, advanced green manufacturing for the entire product chain, and significant improvement of resource utilization and environmental protection. Efficient and refined sorting of multiple-composite solid wastes, precise interface identification and dissociation, and so on, can be achieved by addressing the following technical requirements: 1) developing techniques for *in-situ* nondestructive testing and precise identification of the MCSW interface; 2) developing a full spectrum database of the characteristics of complex materials and multi-dimensional algorithms for accurate identification and sorting; 3) high-efficiency mechanical–physical coupling to enhance dissociation and control at the multi-phase interface; 4) enhanced field control for MCSWs separation technology and equipment; 5) developing integrated treatment technology and equipment for typical MCSWs intelligent identification-interface dissociation-sorting; 6) generating green products via resource recycling and developing “green evaluation” methods and standards for the entire industry chain, i.e., technology–environment–economy; coupling intelligent, green, and precise multi-phase interface control for the entire chain by constructing innovative technological systems.

2.2 Interpretations for three key engineering development fronts

2.2.1 Degradation and recycling of waste plastics

The global cumulative production of plastics has reached 8.3 billion metric tons since the advent of the mass production of plastics in the 1950s, of which 6.3 billion metric tons have become waste, causing great harm to the ecosystem. However, because of the immaturity and high cost of the existing recycling technology, only approximately 9% of the waste plastics can be recycled, and the rest are mostly disposed of by direct incineration, storage in landfills, or discarding; this leads to serious secondary pollution and resource waste. Therefore, developing green and efficient processes for degrading and recycling waste plastics is highly desired.

On one hand, research for developing biodegradable plastics is required to enable plastics to eventually return to nature in the form of CO_2 or water, catalyzed by natural microorganisms; however, this is only applicable in disposal fields where the plastics are difficult to collect. On the other hand, waste plastics can be recycled by four techniques: 1) physical recycling, which often causes a decline in the mechanical properties of the materials because of thermo-mechanical effects, leading to poor performance and low value of the regenerated plastics; 2) biological recycling, which is not yet practical because of the low efficiency of biological enzymes; 3) energy recycling, which usually requires large investment in equipment, and may produce secondary pollution during the recycling process; this process is only suitable for heavily polluted waste plastics; 4) chemical recycling, which has attracted significantly higher attention because plastics can be degraded into useful chemicals through pyrolysis and solvolysis. However, it is hindered by limitations, such as harsh reaction conditions, complex products, and difficulties in product separation and reuse of chemical reagents. At present, recycling is mainly applied to thermoplastics via physical recycling. In comparison, thermoset plastics are difficult to degrade because of their stable three-dimensional network structure; only the reinforcing fibers can be recycled. The recovery of the resin is still in the laboratory stage. Studies on the degradation and recycling of waste plastics include: 1) the development of high-efficiency and high-selectivity chemical degradation catalysts; 2) green and mild solvent systems as well as high-efficiency product separation technologies; 3) novel recyclable plastics with recyclable monomers or reversible dynamic bonds; and 4) low-cost and completely biodegradable plastics.

Future development strategies should focus on application-oriented, closed-loop, and upgrading recycling technologies. Biodegradable plastics should be used in applications where waste plastics are not easy to collect. The impact of environmental factors on the biodegradation of plastic should be considered. Biodegradable plastics that can be rapidly and harmlessly degraded in abandoned environments are in high demand. For applications in which waste plastics are easy to collect, efforts should be strengthened to achieve efficient and clean recovery and to develop technologies for the high-value utilization of waste plastics, including the direct recycling of hybrid plastics, upcycling of waste plastics, and direct conversion of waste plastics to functional/high-performance materials. In addition, recyclable plastics with appreciable thermal stability and mechanical properties are highly desired.

Recycled thermoplastics mainly include polyethylene (PE), polypropylene (PP), polyvinvyl chloride (PVC), polystyrene (PS), and polyethyleneterephthalate (PET). Chinese companies such as Kingfa Sci. & Tech. Co., Ltd. and Longfu Recycling Energy Scientech Co., Ltd., generally use physical recycling to produce regenerative products. Mitsubishi Heavy Industries, Ltd., Kawasaki Heavy Industries, Ltd., JBI Inc., and SITA UK employ chemical recycling and have commercialized pyrolysis technology for oil refining; PET depolymerization has been commercialized by Teijin Ltd., Dupont, Hoechst, and other industries. Recycling of thermoset plastics and composites by physical methods is also used in China. Only a few Chinese companies use chemical pyrolysis to recycle reinforced composite materials. Shanghai Jiao Tong University developed pyrolysis technology and apparatus with completely independent property righs. Three Japanese carbon fiber recycling companies, Toray, Toho Tenax, and Mitsubishi Rayon, and the US companies Carbon Conversions Inc. and MIT LLC, have achieved carbon fiber recycling. Biodegradable plastics include polylactic acid (PLA), poly(butyleneadipate–co–terephthalate) (PBAT), and poly(butyl acrylate) (PBA). Kingfa Sci. & Tech. Co., Ltd. and Xinjiang Blue Ridge Tunhe Chemical Industry Joint Stock Co., Ltd. of China, Natureworks of the United States and BASF of Germany have developed advanced technologies and products. In recent years, China and Chinese enterprises have produced more patents in this field, but have received little attention (Tables 2.2.1 and 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on "degradation and recycling of waste plastics"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	566	90.27%	409	63.02%	0.72
2	South Korea	27	4.31%	14	2.16%	0.52
3	Japan	11	1.75%	30	4.62%	2.73
4	Austria	6	0.96%	76	11.71%	12.67
5	USA	6	0.96%	34	5.24%	5.67
6	India	2	0.32%	17	2.62%	8.50
7	Germany	1	0.16%	57	8.78%	57.00
8	Luxembourg	1	0.16%	4	0.62%	4.00
9	Turkey	1	0.16%	4	0.62%	4.00
10	UK	1	0.16%	2	0.31%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on "degradation and recycling of waste plastics"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Qingyuan Hengjin Plastic Co., Ltd.	China	16	2.55%	4	0.62%	0.25
2	Anhui Guosheng New Material Co., Ltd.	China	12	1.91%	0	0.00%	0.00
3	Jiangsu Jinwo Machinery Co., Ltd.	China	9	1.44%	14	2.16%	1.56
4	Zhangjiagang City Yili Machinery Co., Ltd.	China	8	1.28%	9	1.39%	1.13
5	Jiangxi Fengdi New Materials Co., Ltd.	China	6	0.96%	0	0.00%	0.00
6	Jieshou Rongfa Renewable Resources Co.	China	6	0.96%	0	0.00%	0.00
7	EREMA Engineering Recycling Maschinen und Anlagen GmbH	Austria	5	0.80%	70	10.79%	14.00
8	Fujian Eagle Gifts Craft Production Co., Ltd.	China	5	0.80%	3	0.46%	0.60
9	Shandong Yusu Pipe Co., Ltd.	China	5	0.80%	1	0.15%	0.20
10	Anhui Zhonglu Environment Protection Equipment Technology Co., Ltd.	China	5	0.80%	0	0.00%	0.00

2.2.2 All-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology

With the advantages of low investment and a short construction period, electrochemical energy storage systems have been developed and rapidly promoted in the fields of peak valley price arbitrage, new energy grid connection, and power system auxiliary services. Market-oriented energy storage policies will help promote the market share of electrochemical energy storage to the 100 billion CNY level. At present, LIBs are widely used in new energy power generation. However, the low-temperature discharge capability of traditional LIBs is poor, which makes it difficult to achieve all-climate systems. Moreover, thermal runaway easily occurs under high-temperature abuse conditions. All-climate functional electrochemical energy storage systems based on polymer solid-state lithium battery and lithium capacitor technology are characterized by high specific energy, high safety, a wide operational temperature range, long life, and fast response, making them ideal electrochemical energy storage systems.

A polymer solid-state lithium battery is a battery in which traditional liquid electrolytes are replaced by solid-state electrolytes. The solid-state electrolyte effectively prevents fires and explosions caused by abnormal use of commercial LIBs, such as in situations that induce short-circuiting or pinning. The solid-state electrolyte can also match the high energy density of the lithium anode. Thus, higher energy density can potentially be achieved while meeting the application requirements for high safety. Polymer solid electrolytes have good film-forming ability, high toughness, good compatibility with lithium metal anodes, and are easily produced and processed on a large scale. In 2011, a polymer lithium metal battery with a polyethylere oxide (PEO) solid electrolyte, developed by Bollore Company in France, with an energy density of 170 Wh/kg and good safety performance, was applied in Bluecar and was used in automobile sharing services. In 2015, the Qingdao Institute of Bioenergy and Bioprocess Technology of the Chinese Academy of Sciences developed a polycarbonate-based polymer solid electrolyte. The material has a wider electrochemical window (~4.5 V) and can match the properties of the cathode material, with a higher voltage. The energy density (300 Wh/kg) of solid-state lithium batteries has improved greatly, and the comprehensive performance of these batteries has steadily improved.

The LIC is an asymmetric capacitor in which the charging and discharging principles for the positive and negative electrodes differ. The design of these capacitors exploits the principle of double-layer capacitors and electrochemical lithium storage. The structure combines the negative material of the LIB and the positive material of the electric double-layer capacitor, which greatly improves the energy density relative to that of the traditional electric double-layer capacitor while maintaining high-power characteristics. At present, domestic LICs are in the R&D stage, while foreign LIC manufacturers are active in Japan. Several enterprises, such as JM Energy, FDK Energy, TAIYO YUDEN, ACT Company, and SKEM have initiated batch production. Recently, Maxwell in the United States also developed an LIC with a monomer electrostatic capacity of 2200 F and voltage of 3.8 V, with an energy density of 12 Wh/kg (24.2 Wh/L). Qingdao Institute of Bioenergy and Bioprocess Technology of the Chinese Academy of Sciences successfully developed an LIC with a maximum monomer capacity of 3500 F and voltage of 4 V, with an energy density of 55.9 Wh/L (20.5 Wh/kg). The first pilot production line for LICs in China was designed and constructed.

Japan, China, and South Korea have the largest number of published core patents, with Japan ranking No. 1 with 43.28% and 6.22 citations per patent (Table 2.2.3). It can be seen from Table 2.2.4 that Japanese companies have the absolute “say on patents,” with 6/10 of the main institutions publishing core patents. China has more international cooperation with other countries (Figure 2.2.1).

2.2.3 Manufacturing technology for new-generation shipbuilding steel

Shipbuilding steel refers to the hull structural steel employed in military surface ships (such as destroyers and cruisers) and underwater submarines (such as conventional powered submarines and nuclear-powered submarines), as well as minesweepers. Shipbuilding steel is generally produced

Table 2.2.3 Countries with the greatest output of core patents on “all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Japan	354	43.28%	2 201	59.39%	6.22
2	China	235	28.73%	562	15.16%	2.39
3	South Korea	111	13.57%	322	8.69%	2.90
4	Colombia	57	6.97%	271	7.31%	4.75
5	USA	39	4.77%	336	9.07%	8.62
6	Germany	18	2.20%	40	1.08%	2.22
7	France	3	0.37%	20	0.54%	6.67
8	Belgium	3	0.37%	0	0.00%	0.00
9	Kenya	2	0.24%	9	0.24%	4.50
10	Singapore	2	0.24%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Toyota Jidosha KK	Japan	76	9.29%	302	8.15%	3.97
2	Idemitsu Kosan Co., Ltd.	Japan	56	6.85%	233	6.29%	4.16
3	TDK Corporation	Japan	28	3.42%	185	4.99%	6.61
4	Samsung Electronics Co., Ltd.	South Korea	28	3.42%	183	4.94%	6.54
5	LG Chem Ltd.	South Korea	28	3.42%	70	1.89%	2.50
6	Furukawa Kikai Kinzoku KK	Japan	22	2.69%	18	0.49%	0.82
7	Panasonic Intellectual Property Management Co., Ltd.	USA	21	2.57%	92	2.48%	4.38
8	Hitachi Ltd.	Japan	19	2.32%	89	2.40%	4.68
9	Seiko Epson Corporation	Japan	16	1.96%	130	3.51%	8.13
10	Korea Institute of Industrial Technology	South Korea	14	1.71%	14	0.38%	1.00

in small batches, must meet various specifications and high requirements, and is characterized by slow updates. Moreover, it is essential for shipbuilding steel to display sufficient strength and toughness and excellent workability, while resisting corrosion by seawater. All countries worldwide have strict requirements on the quality of ship steel, not only in terms of the chemical composition and mechanical properties, but also quality control during the production process.

With the development of manufacturing technologies such as ultra-pure smelting, micro-alloying, controlled rolling, and cooling, and to improve the welding properties and reduce the welding cost of ship steel, the United States developed a new generation of HSLA ship-hull steel. They implemented the industrial production of HSLA80 steel and HSLA100 steel after carrying out the industrial TMCP and accelerated cooling tests with Japanese steel enterprises in the 1980s. In the early the 1990s, HSLA65, HSLA115, and HSLA130 steels were developed and applied to the main housing, aircraft deck, trestle deck, and the key structural parts of surface ships to further reduce the weight and lower the center of gravity for new aircraft carriers. HSLA hull steel, based on low-carbon ferrite steel or ultra-low-carbon bainite steel, has a lower carbon content and excellent weldability and low-temperature toughness compared with the conventional quenched and tempered hull

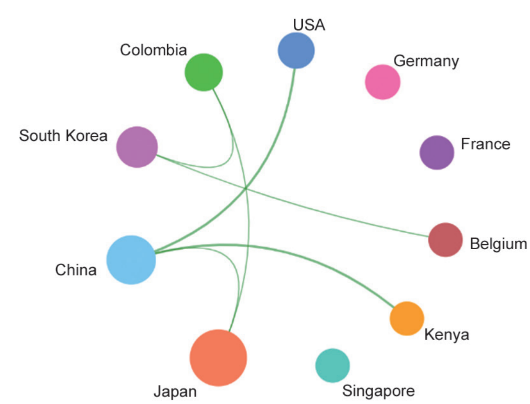

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "all-climate electrochemical energy storage systems based on solid-state lithium battery and lithium capacitor technology"

steel. Copper aging treatment and precipitation strengthening are used to compensate for the strength loss caused by carbon reduction. This type of steel can be welded at 0 °C without preheating, which greatly simplifies shipbuilding processes, and it represents the development trend for new-generation structural hull steel. Many advanced countries worldwide have also developed new ship steel: Russia developed AB series steel, with a yield strength of 1 175 MPa; Japan developed NS110 steel, with a yield strength of 1 078 MPa; and France developed HLES100 steel, with a yield strength of 980 MPa. The United Kingdom and Australia have also developed HSLA steels with strength and toughness equivalent to those of US HY100 steel.

High performance remains the main pursuit of new-generation shipbuilding steel. It is crucial to enhance its overall characteristics, such as strength, shape, toughness, and anti-explosion performance, as well as anti-brittle damage, anti-seawater corrosion, and anti-fatigue properties. Strict specifications and dimensions are required for ship plate steel, and the use of this steel affords finished products with higher quality. High surface quality is required, with no surface defects and a compact and uniform surface oxide scale. Much attention has been paid to tailoring the composition of high-strength structural steels and strengthening methods, such as precipitation strengthening with nanoscale precipitates based on conventional alloying, and to improving the theories and methods. Balanced improvement of the service and welding performance has received much more attention, along with high strength and toughness.

Asian countries, especially China, witnessed rapid development during the last 30 years. The countries and institutions with the greatest output of core patents on “manufacturing technology for new-generation shipbuilding steel” since 2014 are listed in Tables 2.2.5 and 2.2.6, respectively. The collaborative network among major countries focusing on “manufacturing technology for new-generation shipbuilding steel” is illustrated in Figure 2.2.2. According to Table 2.2.5, the majority of the core patents were published by the top five countries (China, Japan, South Korea, the United States, and Germany). China’s output of core patents accounted for 40.67% of the total, and Japan ranked second, with their output accounting for 38.66%. Patents from Japan had the highest number of citations (1 374), and the percentage of citations reached 53.05%, far exceeding those of other countries. The average citation rates for France and the United States ranked among the highest worldwide. According to Table 2.2.6, the top 10 institutions with the greatest output of core patents are five Chinese companies, three Japanese companies, and two South Korean companies. The top three of the 10 are all Japanese companies. In the development of new-generation shipbuilding steel, considerable attention should be paid to the development trends in Japan, the United States, and Germany, especially Japanese enterprises. As illustrated in Figure 2.2.2, only Germany, Sweden, and South Korea collaborated in the development of new-generation shipbuilding steel.

Table 2.2.5 Countries with the greatest output of core patents on “manufacturing technology for new-generation shipbuilding steel”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	242	40.67%	404	15.60%	1.67
2	Japan	230	38.66%	1374	53.05%	5.97
3	South Korea	40	6.72%	98	3.78%	2.45
4	USA	23	3.87%	231	8.92%	10.04
5	Germany	17	2.86%	133	5.14%	7.82
6	Russia	7	1.18%	3	0.12%	0.43
7	France	6	1.01%	71	2.74%	11.83
8	UK	5	0.84%	5	0.19%	1.00
9	Netherlands	3	0.50%	26	1.00%	8.67
10	Sweden	3	0.50%	21	0.81%	7.00

Table 2.2.6 Institutions with the greatest output of core patents on "manufacturing technology for new-generation shipbuilding steel"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Nippon Steel & Sumikin Stainless Steel Corporation	Japan	82	13.78%	582	22.47%	7.10
2	JFE Steel Corporation	Japan	74	12.44%	403	15.56%	5.45
3	Kobe Steel Ltd.	Japan	50	8.40%	226	8.73%	4.52
4	Baoshan Iron & Steel Co., Ltd.	China	22	3.70%	38	1.47%	1.73
5	Posco Co., Ltd.	South Korea	17	2.86%	45	1.74%	2.65
6	Nanjing Iron & Steel Co., Ltd.	China	12	2.02%	28	1.08%	2.33
7	Angang Steel Co., Ltd.	China	12	2.02%	17	0.66%	1.42
8	Hyundai Motor Co., Ltd.	South Korea	8	1.34%	29	1.12%	3.63
9	Tangshan Iron and Steel Group Co., Ltd.	China	8	1.34%	4	0.15%	0.50
10	China State Shipbuilding Co., Ltd.	China	7	1.18%	3	0.12%	0.43

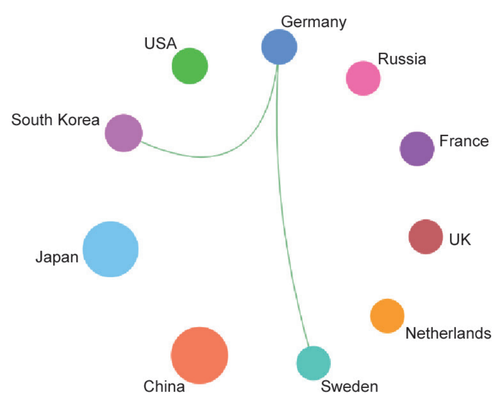

Figure 2.2.2 Collaboration network among major countries in the engineering development front of "manufacturing technology for new-generation shipbuilding steel"

Participants of the Field Group

Directors

WANG Jingkang, LIU Jiongtian

Deputy Directors

LI Yanrong, LIU Zhongmin, MAO Xinping, NIE Zuoren, TAN Tianwei, ZHOU Yu, Qu Lingbo, YUAN Yingjin

Members of the Working Group

CHEN Biqiang, DENG Yuan, WANG Cong, YAN Yichao, YANG Zhihua, YE Mao, ZHANG Huili, LI Daxin, WANG Jing, WANG Jingtao, XI Xiaoli, YAO Changguo, ZHU Wei, CHENG Luli, GAO Yanjing, HUANG Yaodong, LI Yanni, TU Xuan, WANG Aihong, ZHANG Yuanjing, ZHU Xiaowen

Report Writers

CHANG Jiang, CHEN Ruirun, LI Daxin, QI Yu, RONG Qian, SUN

Mingyue, SUN Zhi, TANG Xinjing, WANG Cong, WANG Qiang, WANG Tongmin, XU Shimei, YAN Yichao, YAO Changguo, ZHONG Yunbo, ZHU Xiaowen, ZHU Wei

Acknowledgement

We are grateful to the following scholars for their contributions to the project.

Central Research Institute of China Baowu Steel Group

GU Haifang, WANG Yuan

Beihang University

FENG Jingjing, HAN Guangyu, WANG Yaling, ZHANG Qingqing, ZHOU Jie

Beijing University of Chemical Technology

MA Zhiyong, SHEN Chun, WANG Dan, WANG Guirong, WANG Meng, YUAN Zhiqin

Dalian Institute of Chemical Physics, Chinese Academy of Sciences

BAI Yu, GAO Dunfeng, HU Yanming, LI Xianfeng, WANG Yu, ZHANG Fuxiang

University of Electronic Science and Technology of China

LI Jie, PENG Bo, QI Jingbo, BI Lei, WANG Xianfu, WU Chunyang

Northeastern University

LIU Tie, WANG Jianfeng, YUAN Shuang

Harbin Institute of Technology

HE Peigang, JIA Dechang

Sichuan University

WANG Xiuli, WANG Yuzhong

Tianjin University

HOU Jinjian, QIAO Jianjun

Central South University

TIAN Qinghua

Northwestern Polytechnical University

WANG Haipeng

Kunming University of Science and Technology

ZHANG Libo

Chongqing University

LV Xuewei