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# Preliminary Study on Impact of Disruptive Technologies in Chemical, Metallurgical, and Material Fields

**The Research Group of *Chemical, Metallurgical, and Material Fields***

**Abstract:** The chemical, metallurgical, and materials industries reprocess natural resources to produce materials, chemicals, and secondary energies necessary for human life; thereby, they provide an important material basis for social development and economic construction. This paper reviews the recognized disruptive technologies in the history of chemical, metallurgical, and material industries, and analyzes the impact of similar technologies on the daily lives of individuals, progress of human society, and disruption of traditional technologies. According to the overall vision, problem orientation, and worldwide trend of technology development, we forecast the models for future sustainable science development that are efficient, safe, energy-saving, and environment-friendly, in the chemical, metallurgical, and material industries. Furthermore, we predict the impacts of likely disruptive technologies on the national economy and individuals' livelihood. The slurry bed hydro-conversion technology, the metallurgical manufacturing process function expansion technology, grapheme engineering, and other disruptive technologies are proposed. Finally, relevant policies and recommendations are proposed for cultivating and developing an environment favorable to disruptive technologies.

**Keywords:** chemical industry; metallurgy; material; disruptive technology; national economy and people's livelihood

## 1 Introduction

Energy, food, and materials are the basis for human survival and development. Technological advancements in the fields of chemicals, metallurgy, and materials have effectively guaranteed the evolution of human civilization. The Stone Age, Bronze Age, and Iron Age are named after the prominent material in use by humans of those eras. A variety of modern materials have become an important basis for the development of human society. Various fertilizers, pesticides, and chemical fiber fabrics have increased the supply of food and clothing, satisfying the requirements of an increasing population. Moreover, various oils have provided sufficient power for modern vehicles. The chemical and metallurgical industries are the mainstay of manufacturing and the national economy, which guarantee the survival and development of the country [1].

The chemical, metallurgical, and material industries conduct chemical and physical processing by acquiring natural resources, to produce diversified materials, chemicals, and secondary energy that satisfy the requirements for a fulfilling life. However, owing to a lack of cognition, technical limitations, and focus on short-term benefits, there is also excessive development and wastage of resources; this is resulting in environmental pollution and excessive carbon dioxide emissions. With the advancements in science and technology and the deepening of cognition, humans are beginning to pay attention to sustainable development of society. In addition, they are demanding the chemical, metallurgical, and materials industries that process natural resources, to vigorously promote scientific and technological progress and achieve sustainable development that is green and low-carbon. In the past few decades, the chemical, metallurgical, and material sectors in China have achieved significant

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**Corresponding author:**Sun Jiquan. E-mail: sunjq@ustb.edu.cn

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milestones and contributed extensively to the rapid development of China’s national economy. However, a disparity remains between China and the developed countries. We must identify another method to match them. Research on disruptive technology should be hastened. It is necessary to sensitively identify, capture, and cultivate disruptive technologies exerting a strategic impact on economic and social development and on national defense; this will aid in strategically initiating new technological changes and ensure a dominant position in the world’s competitive landscape. In accordance to this requirement, we reviewed the disruptive technologies and influences in the chemical, metallurgical, and material engineering fields and studied the background and conditions for the emergence and development of disruptive technologies. According to the vision driving, problem orientation, and the worldwide trend of technology development, the likely direction for future development of these three engineering fields is proposed; moreover, the disruptive technologies likely to appear in the future is listed.

## 2 Disruptive technologies and their impact on the chemical, metallurgical, and material engineering fields

Historically, disruptive technology in the fields of chemical, metallurgical, and material engineering has supplanted the traditional production technology in these fields and has also profoundly impacted other fields as well as human life.

### 2.1 Chemical engineering field

Disruptive technology in the chemical engineering field emerged from the mid-19th century to the mid-20th century; the period witnessed the second industrial revolution and the two world wars. During this period, the population increased rapidly, the economy developed speedily, the advancement of science and technology accelerated, and human lifestyle underwent tremendous changes. The field has become an important promoter of disruptive technology from germination to actualization. As an important area that underwent scientific and technological progress in the second industrial revolution, the petrochemical industry provides a strong foundation for social development in terms of material and energy availability. It is closely related to people’s food, clothing, housing, and transportation and significantly impacts social development and human life. The birth of disruptive technology has substantially satisfied the demand for petrochemical technology and products for social development; moreover, it has played a positive role in improving people’s lifestyle and quality of life. However, disruptive technology in the chemical industry depends on the adoption of a new development track. It has achieved tremendous breakthrough and influence, affected numerous related industries, and has resulted in unprecedented productivity for human society [2].

#### 2.1.1 Transformed people’s lifestyles and promoted social civilization

Disruptive technology has changed the way people travel. The birth of technologies such as catalytic cracking has satisfied the demands of the military establishment and the automobile industry for gasoline, diesel, jet fuel, and other fuels by enabling their large-scale production. Through continuous technological advancement that enabled gradual improvement in its economic viability and product practicability, petroleum-refinery products replaced coal and rapidly became the main transportation fuel—it was the advent of the oil era [3]. Disruptive refining technologies such as fluid catalytic cracking have transformed the way people travel, significantly facilitating people’s logistical activities [4].

Disruptive technology has altered the historical course of world food production. Synthetic ammonia industrialization technology is recognized as one of the most important inventions in the field of chemistry. With the industrialization in the early 20th century, while the world population increased to 4.5 times, food production increased to 7.7 times. According to the statistics of the Food and Agriculture Organization (FAO), the application of chemical fertilizers accounts for 50% of the world’s food production. Effectively, without the invention of synthetic ammonia, 50% of the present population would have remained hungry. Thus, synthetic ammonia industrial technology has made a substantial contribution to world food security and human survival and development; it continues to occupy an irreplaceable position.

Disruptive technology ensures that humans obtain materials necessary for life, such as those for clothing and accommodation. The world’s population is growing rapidly; as a consequence, the supply of natural dyes, fibers, rubber, etc., is no longer able to satisfy the rapidly growing market demand. The invention of synthetic dyes and three major synthetic chemical technologies has made petrochemicals the major sources of dyes, fibers, rubbers, and resins; effectively, this enabled the use of the abundant petroleum resources to provide sufficient material for

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rapid population growth. The performance of synthetic dyes, fibers, and resins has been largely superior to that of natural materials, bringing about a revolution in clothing and construction materials. The application of clothing and accommodation is no longer limited to providing protection against environmental extremities; it has been extended to providing aesthetics, which has substantially improved the quality of life.

#### 2.1.2 Changed the original production methods, increased productivity, and promoted industrial transformation and the energy revolution

Thermal cracking technology has resulted in the development of petroleum refining from primary processing to secondary processing, from physical transformations to chemical reactions. Catalytic cracking technology transforms the petroleum refining process from thermal processing to catalytic processing. These technologies have significantly improved crude oil utilization and produced petroleum-based chemical raw materials. By utilizing the superior characteristics of catalytic reactions, the light-oil yield of crude oil has increased to over 70%; moreover, the high proportion of isomerized component in the product effectively improves the octane number of gasoline and stability of diesel. Hydrocracking technology can process heavy oil, which is difficult to be converted by catalytic cracking. The produced naphtha exhibits a higher octane number, and the aviation kerosene and low-condensation diesel that are produced exhibit higher combustion performance and stability. In addition, the tail oil produced can be used as a raw material for lubricating oil. Hydrogenation technology improves the utilization of raw materials and is an important method for increasing the production of naphtha, jet fuel, and clean fuel [5].

Disruptive technology altered the approach toward production. Continuous distillation achieves continuous operation in time and space, thereby substantially improving efficiency and reducing production costs. It laid the foundation for the petrochemical industry to become a process industry. Hydrogenation technology advanced beyond the reaction concept of the original refining technology. It introduced a hydrogen source; improved raw material adaptability, product cleanliness, and economy; and is a key technology for the refining industry to overcome the challenges of resource alterations and environmental protection restrictions. Since the 1920s, petrochemical technology to produce ethylene and aromatics from naphtha has supplanted the traditional technology of producing organic chemicals from coal. At present, ethylene production is a measure of the level of development of a country’s petrochemical industry [6].

### 2.2 Metallurgical engineering field

In the 1860s, mechanization promoted the rise of the first industrial revolution. The manufacture of machines required a large amount of metal materials, which also promoted the rapid development of the metallurgical industry. The metallurgical industry can be divided into two major categories: the ferrous metallurgical industry (i.e., the steel industry) and the nonferrous metallurgical industry. During the evolution of the metallurgical production processes in the 20th century, the disruptive technologies involved were oxygen converters and continuous cast steel for the first category and large-scale prebaked cells and continuous extrusion of electrolytic aluminum for the second category.

#### 2.2.1 Altered human lifestyle and promoted the progress of social civilization

Metal is the most important material basis for human civilization, particularly agricultural civilization and industrial civilization. Since the Bronze Age, metals have been an important material for the production of tools and weapons. The level of metal smelting determines the development of social productivity. The rapid progress of the industrial revolution brought forth the emergence of converter and flat furnace steelmaking technology in the mid- and late-19th century. In particular, the disruptive emergence of oxygen top-blowing converters and continuous casting in the mid-20th century marked the arrival of the modern steel era [7,8]. Meanwhile, the Bayer process for alumina, aluminum electrolysis, copper flash smelting, and zinc hydrometallurgy (as examples) rapidly advanced the non-ferrous metal industry. Consequently, aluminum, copper, lead, zinc, and other metals have become widely-used materials. Rare metals and precious metals are also being industrially produced on a large scale [9]. In the material industry, metal materials have always dominated both as structural materials and functional materials (related to conductivity, electromagnetism, anti-corrosion, etc.).

Owing to the rapid development of various complex technologies, at present, metal materials find application in aerospace, defense, transportation, household appliances, and even culture and art. This demonstrates that metal materials have already been integrated into people’s daily lives. In particular, the popularity of high-rise buildings and family cars has completely altered people’s approach toward life and travel. All these are inextricably linked to the disruptive technological developments in the metallurgical field described above.

### 2.2.2 Altered the original production mode, increased productivity, and promoted energy conservation and environmental protection

Oxygen top-blown converter steelmaking is a steelmaking method. Since its incorporation into industrial production in the early 1950s, it has been rapidly promoted worldwide. It completely substantially replaced air converter and flat steelmaking (the traditional steelmaking process) to become the main method of steelmaking. By blowing an appropriate amount of oxygen from the top of the converter for agitation, the smelting process can be enhanced, metallurgical conditions improved, metal yield and production efficiency improved, and raw material consumption reduced. It has high significance with regard to improvement in the quality of molten steel and reduction in energy consumption. Therefore, the oxygen top-blown converter steelmaking process is a significant disruptive technology in the field of iron and steel metallurgy [10].

In the production of various types of steel products, there are two methods for solidifying molten steel: traditional die casting and continuous casting. In the 1950s, European and American countries successively developed continuous casting technology to directly cast molten steel. The continuous steel casting technology is a casting process in which molten steel is continuously passed through a water-cooled crystallizer, solidified into a hard shell, continuously drawn out from the lower outlet of the crystallizer, cooled by water spray, solidified, and cut into blanks. Compared with the ordinary steel ingot die casting, it exhibits the advantages of enhanced production efficiency, increased metal yield, energy savings, reduced emissions, improved quality of the slab, improved operating conditions, and convenient mechanization and automation. After the two energy crises of the 1970s, energy prices increased, which strongly promoted the development of continuous casting technology. At present, except for a marginal amount of special steel, continuous casting production has been realized for all steel production; this has completely supplanted the traditional mold casting production, significantly reduced cost, substantially improved production efficiency and production scale, and altered the development mode of the steel mill [11].

In recent decades, the production efficiency of the non-ferrous metal industry has improved substantially. High-efficiency Bayer alumina production and large-scale electrolytic aluminum prebake cell technology have resulted in significant improvements in primary aluminum production and have reduced energy consumption. Copper-rich oxygen flash smelting and molten pool smelting also minimally affect the environment while ensuring large-scale production. New hydrometallurgical processes such as pressure leaching, solvent extraction, ion exchange, biometallurgy and new electrolysis technologies increase the production efficiency of zinc, copper, nickel, cobalt, many rare metals and precious metals, greatly reducing the cost. The large-scale, continuous, and automated equipment in the production process of the non-ferrous metal industry was gradually promoted. Continuous extrusion technology has been widely used in the field of non-ferrous metals because it does not entail extrusion allowance and exhibits high material utilization rate, high product yield, high production efficiency, and low energy consumption; thereby, it supplanted the traditional long product processing [12].

## 2.3 Material engineering field

Materials form the basis for human civilization and social progress. The utensils used by humans are made of various materials. The industrial revolution and the development of science and technology have resulted in the continuous renewal of materials; new materials are constantly emerging, and the new types of materials are more diverse [13].Typical examples of disruptive technologies have emerged in advanced structural materials, biomedical materials, high-performance fiber materials, new energy materials, inorganic nonmetallic materials, rare earth materials, superconducting materials, sensing materials, and graphene materials. The following are examples of advanced structural materials, biomedical materials, and new energy materials; they illustrate the transformations that disruptive technologies bring to people’s lifestyle and production methods.

### 2.3.1 Altered people’s lifestyle and promoted social civilization

Ultra-supercritical thermal power units are the most important components of the world’s power generation system. The high-capacity, high-efficiency, low-energy, and high-steam-velocity of ultra-supercritical power stations are highly likely to key aspects in the future development of China’s electric power systems. The development of high-strength and long-life iron-based, iron-nickel-based, and nickel-based heat-resistant materials and the manufacture of key components are the critical issues with respect to ultra-supercritical thermal power units. It is the key to improving the efficiency of thermal power units and the safe and reliable operation of power stations. Its large-scale application can reduce coal consumption and reduce the emission of pollutant gases such as

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carbon dioxide.

Biomedical materials are new high-tech materials used to diagnose, treat, repair, and replace or improve the function of a diseased tissue or organ. It is the basis for the study of artificial organs and medical devices and has become an important branch of materials science. Its application saves the lives of tens of millions of critically ill patients and substantially improves human health and quality of life [14].

New energy materials mainly include materials for solar cells, hydrogen storage, and fuel cells. In this paper, the authors have selected thin-film solar cell material technology and high energy-density lithium ion power battery material technology as typical cases of disruptive technology. Solar cells are devices that convert solar energy into electrical energy through the photovoltaic effect; they enable an important form of utilization of solar energy. A thin-film solar cell is a solar cell with an optoelectronic functional film as an absorption layer. The absorption layer material is used in a marginal amount, and the production cost is low. Moreover, a flexible substrate can be used, which makes it convenient to realize photovoltaic building integration [15].

Although China has a large number of cars, we lack independent intellectual property rights on the core technology of internal combustion engine vehicles. However, in terms of electric vehicles, our technical capabilities are comparative to those of other countries. Moreover, certain disruptive technology has been developed in the field of high energy-density lithium ion power battery materials. Their remarkable technical economy and competitive strength aid in realizing a rapid development of China’s auto industry vis-à-vis traditional auto powers; these two aspects also have long-term strategic significance for China’s economic development and the enhancement of international competitiveness.

### 2.3.2 Altered the original production mode, increased productivity, and promoted energy conservation and environmental protection

The disruptive technology in the field of new materials has significantly impacted daily human life, plays an important role in the promotion of economic and social development, and is a key driver of strategic competition among the world’s technological powers. The following are example of similar technology including 3D printing, superconducting materials, graphene and other new two-dimensional materials, and material genetic engineering.

An emerging technology in the manufacturing field, 3D printing technology has revolutionized the field of material engineering. Materials are a core technology of the 3D printing process. The 3D printing process involves both the forming process and the process of manufacturing of the material. The extensive participation of material technology enables the material process to be embedded in the 3D printing process for realizing the simultaneous development of materials and forming processes. 3D printing is widely used in machinery manufacturing, medical, construction, automotive manufacturing, and other industries. A breakthrough in the preparation technology of metal powder materials is the key to the future 3D printing technology for high-end manufacturing.

Superconducting materials exhibit zero resistance, complete diamagnetism, and macroscopic quantum effects unavailable in conventional materials. It is one of the most important research directions in contemporary condensed matter physics as well as an active and important frontier in the field of new materials. It is closely related to a series of fundamental scientific issues of high significance in condensed matter physics. Superconducting application technology is accompanied by breakthroughs in material preparation technology, continuous improvement in material properties, and reduction in the cost of low-temperature systems. It has been in preparation for large-scale application breakthroughs. The wide application of superconducting materials can save energy and reduce carbon dioxide emissions; moreover, it plays an important role in the promotion of technology upgrades in the energy conservation and environmental protection industries.

Studies on graphene and the other new two-dimensional materials are at the forefront of research in the field of condensed matter physics and materials science. The preparation of large-size, high-quality two-dimensional materials is very important for exploring new physical phenomena and performance; furthermore, it has substantial application value in electronic and optoelectronic devices of the future. In recent years, research on two-dimensional materials such as transition metal sulfides and transition metal carbides represented by phosphorene, silicene, germanene, hafniumene, stanene, boron nitride, indium selenide, and molybdenum sulfide have made certain progress. In the future, device applications based on two-dimensional materials are likely to advance beyond the limitations and challenges faced by traditional semiconductor processes and promote innovation and development in the field of micro-nanoelectronics.

Material genetic engineering is altering the traditional research and development model and approach toward materials. It aids in developing new materials rapidly with low consumption and highly effective innovation. Its key issue is the establishment of a high-throughput automated process calculation model that combines high-throughput material design, manufacturing, and testing as well as a material database. Through modeling and calculation, the quantitative representation of material composition design, structure prediction, processing preparation, and service behavior and process were realized; this revealed the related mechanism and internal law between the material chemical factors and structural factors and material properties and functions, which can provide a scientific basis for developing new materials and realizing on-demand design materials.

## 3 Prospects

Future economic development should be a scientific development model that is efficient, safe, environment friendly, and sustainable. The disruptive technologies in the fields of chemical, metallurgical, and material engineering, which are the foundational industries of the national economy, play a prominent role in the production methods of these industries and substantially impact other industries.

### 3.1 Chemical engineering field

At present, China’s economic development is in the “new normal” era, where higher attention is paid to the quality of development, environmental protection, and resource conservation. The achievement of clean energy production, efficient use of energy and resources, and opening-up of important infrastructures for petrochemical raw materials are the main challenges confronting the clean and sustainable development of China’s petrochemical industry. Slurry bed residue hydro-conversion technology and the technology for producing olefin/aromatics directly from methane are likely to become disruptive technologies in China’s chemical industry.

Slurry bed hydrocracking technology takes into account economy and cleanliness. It is the key technology for the clean and efficient conversion of heavy and inferior crude oil in the future. It represents the advanced level of the refining industry and has broad application prospects. As slurry bed residue hydro-conversion technology continues to mature, it will gradually replace the inferior residue processing technology that provides low yield of light oil (e.g., coking). The large-scale industrial application of slurry bed residue hydro-conversion technology will significantly improve the utilization of petroleum resources and the cleanliness of products and residue processing. It will significantly promote the refining industry to achieve green and low-carbon and transformational development and positively impact the human living environment [16].

The technology for producing olefin/aromatics directly from methane includes the technology for oxidative coupling of methane to ethylene and anaerobic conversion of methane to olefin/aromatic. The technology of oxidative coupling of methane to ethylene has experienced rapid development in its beginning, decline, and rejuvenation phases; it is now entering the industrial demonstration stage. The anaerobic conversion of methane to olefin/aromatics is still in the laboratory research stage. The technology for direct production of ethylene/aromatic from methane will supplant the traditional ethylene/aromatic production model using naphtha as raw material; moreover, it will alter the structure of available petroleum products and determine a new resource route for the production of basic petrochemical raw materials. It will play an important role in expanding the source of China’s petrochemical raw materials and satisfying the growing demand for petrochemical products in China. Furthermore, the new technology route has a comparative advantage in terms of the utilization efficiency of carbon atoms; this favors the transformation of the petrochemical industry toward being green and low-carbon.

### 3.2 Metallurgical engineering field

In the more recent stages of industrialization, resource scarcity, energy crisis, and environmental degradation have become increasingly severe; moreover, the development of the metallurgical industry has been seriously challenged. However, it has also provided opportunities for the development of the existing metallurgical industry. Under the guidance of metallurgical process engineering, the function of metallurgical manufacturing process expanded; in addition, its waste recovery and recycling functions are being utilized to develop economic linkages with other industries or society. On the one hand, waste is converted into a resource, which can reduce emissions by industry and eliminate urban waste. On the other hand, waste recycling and high-value utilization are sought, which aid in satisfying the waste discharge requirements and increasing the value of waste; thereby, the production mode of the traditional metallurgical industry can be converted into a circular economy development model for green production. The application of the circular economy development model of the metallurgical industry will affect the emission quantities and emission patterns of wastes from the metallurgical manufacturing processes. The relationship between the metallurgical industry and other industries as well as that between metallurgical enterprises and cities/society will also be affected. The concept of a circular economy development model for

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green production has been accepted and applied by most steel mills (e.g., blast furnace slag is supplied for cement production and the byproduct gas is supplied for producing chemical products); however, it has not caused a subversive impact. Non-ferrous metallurgical enterprises innovated green non-ferrous metallurgy technology capable of efficient separation and extraction; using this technology, the toxic and hazardous elements in raw materials (including secondary resources and ore) are converted to resources or made as harmless as feasible, minimizing the impact on the environment [17].

In addition, under the present trend of de-capacity in the steel industry, scrap steel resources will gradually become more enriched; this in combination with the constraints on iron ore resources, provides a resource premise for the development and application of electric steelmaking technology. The new electric furnace technology in the era of low carbon steel (scrap steel) will become an innovative means for altering the available traditional production process in the ferrous metallurgy industry. It will have an important impact on China’s steel industry’s process structure, model, and distribution as well as on ferrite resource consumption, energy consumption, and carbon emissions [18].

The disruptive technology in the field of alumina production is zero-emission clean production alumina technology. First, the technology theoretically circumvents the Bayer process’ limitation to bauxite aluminum-silicon grade; it can produce alumina from low-grade bauxite. Second, it has significantly reduced the content of sodium and aluminum in red mud; this fundamentally enables large-scale, low-cost, and non-hazardous resource-recycling of red mud. As a result, zero-emission and clean technology for alumina production and low-cost, large-scale red mud consumption technology have been developed and refined; these have significant economic benefits and prospects for effective application.

### 3.3 Material engineering field

President Xi Jinping once indicated that materials are the basis of manufacturing. At present, China’s advanced high-end material research and development and production are significantly below par of the developed countries; moreover, the key high-end materials are not self-sufficient. Therefore, the development of advanced high-end materials such as graphene and metamaterials is urgent.

Graphene is an allotrope of carbon. Although its structure is simple, it has a series of remarkable physical and chemical properties, which endow graphene with the potential to bring about a series of disruptive technologies in numerous fields. These disruptive technologies can strongly support the performance improvement and application of a large number of traditional materials. Its application in new energy, petrochemical, electronic information, composite materials, and biomedicine will cause transformations in related industries. Furthermore, it will become a new material at the strategic frontier that will lead the new generation of industrial technology revolution and future high technology competition [19].

Metamaterial refers to artificial materials obtained by artificial structures with extraordinary properties not exhibited by natural materials. In recent years, the development of metamaterials has gradually shifted from the fields of electromagnetics to those of mechanics, acoustics, thermals, and mass transfer. A series of new metamaterials with extraordinary properties and unusual functions have emerged one after another. Among these, electromagnetic stealth materials have gained significant attention. Metamaterial stealth technology guides the electromagnetic wave diffraction propagation by preparing the metamaterial cover, to achieve stealth; this will transcend the stealth means of reflecting and absorbing electromagnetic waves. Because these materials provide a number of new features that discredit traditional theories and common sense, they can result in the birth of a new series of disruptive technologies.

In summary, the chemical, metallurgy, and material engineering fields provide safe, environment friendly, and reliable green materials for all aspects of life. They have significantly altered people’s lifestyle and are highly likely to make more significant contributions to the progress of human civilization in the future.

## 4 Policy recommendation

### 4.1 Strengthen fundamental science research

Fundamental theoretical research and original innovation together form the source of disruptive technologies. Without the accumulation of fundamental research, there will be no capability to develop and refine disruptive technologies. Therefore, it is challenging for industrial development to progress to a higher level without effective support. We should further strengthen progressive and application-oriented research and lay a strong scientific and technological foundation for the emergence of new materials and processes in the chemical, metallurgical, and material engineering fields. An improvement in the competitiveness of fundamental research in these fields is conducive to the solution of key scientific problems confronting the national economy and social development; moreover, it can also promote the emergence and development of disruptive technologies through advancements in fundamental theory.

### 4.2 Attach importance to interdisciplinary study

Human society is confronting increasingly complex development problems, generally challenging to solve with a single discipline. Therefore, interdisciplinary study is receiving increasing attention. To highlight the interdisciplinary integration, it is necessary to consider the upstream and downstream integration of scientific and technological innovation and the integration of different disciplines; in addition, it necessary to conduct research in interdisciplinary fields in order to achieve original results with disruptive significance. It is necessary to fundamentally overhaul the scientific research management and the subject-organization mode of the original division of disciplines, and create a set of interdisciplinary, open, and shared operation mechanisms. All disciplines should cooperate to address problems and cultivate scientific research talent. Emphasis should be placed on engineering design and engineering technology research on the production and transformation of materials. New technologies within the chemical, metallurgical, and material engineering fields are to be integrated for them to contribute to the emergence and development of disruptive technologies. Furthermore, other fields that provide raw materials and fuels can also be integrated to promote the emergence of disruptive technologies.

### 4.3 Create a growing environment for disruptive technology

It requires the necessary fundamental technology accumulation for disruptive technology to leap from germination, which is a long-term process with uncertainties. Therefore, it is necessary to strengthen the top-level design and establish a long-term research mechanism for disruptive technologies. It is important to establish a more flexible and tolerant disruptive technology development environment, and to optimize the screening and review mechanism of scientific research projects. We should create an innovative atmosphere that exhibits the courage to challenge authority, tolerates failure, and explores freely. We should encourage researchers to courageously surpass available technology systems and models to experiment with new research concepts. We should inspire the creativity of researchers. We should create a situation that is suitable for disruptive technology and that can guarantee the time and technology accumulation required for disruptive technology development.

### 4.4 Pay attention to technology accumulation and investment

The development of disruptive technology arises from the integration of technologies in various fields or the breakthroughs after the deepening of traditional technologies. In the absence of the necessary accumulation of application technology, even if the potential direction of disruptive technology is identified, it is challenging to achieve continuous improvement and breakthroughs; therefore, technological accumulation must be completed effectively. The inadequate development of key fundamental materials, advanced fundamental processes, and quality technology foundations constrains the development of China’s chemical and metallurgical industries and is also a key shortcoming stalling the development of aviation, aerospace, and transportation. Therefore, we should focus on the requirements of national projects of high importance; strengthen the accumulation of application technologies in the chemical, metallurgical, and material engineering fields; increase support, particularly for the potential ones from among certain unpopular technological innovation projects; and promote fundamental research in the chemical and metallurgical engineering fields.

### 4.5 Establish scientific criteria

Early prediction and identification of disruptive technologies are key to conducting disruptive technology research. However, its criteria and method of evaluation are a double-edged sword. When used well, it can promote the cultivation and development of disruptive technologies. Whereas, poor use will hinder or even abort disruptive technologies. Therefore, it is recommended that the chief authorities further strengthen theoretical research; improve the progressive orientation of science and technology policy formulation; and gradually establish the identification methods, cultivation mechanism, and evaluation criteria of disruptive technologies; thereby, their evaluation can be more scientific so as to enable the implementation of progressive strategic measures consistent with the latest developments worldwide. In accordance with the major requirements of national economic and social development, and the developmental trend of science and technology, we should focus on ensuring national competitiveness in the future, be at the forefront of scientific progress, focus on the front-end of the innovation chain, and strategically deploy the industrial chain in advance.

### 4.6 Inspire the enthusiasm of scientific and technical personnel

Talent is an important support for building a great country with competitive capabilities in science and technology. The report of the 19th National Congress of the Communist Party of China indicated the necessity of cultivating a large number of strategic and technological talents, leading scientific and technological talents, young scientific and technological talents, and high-level innovation teams of international standards. Sufficiently inspiring the enthusiasm of scientific and technological personnel is necessary for the formation of disruptive technologies; moreover, it can reliably guarantee China’s position at the forefront of innovation across the world. We should stimulate sustained innovation by science and technology personnel, speedily reform the scientific research project management mechanism, reduce the red tape, and let the scientific and technical personnel apply more efforts in research. It is necessary to speed up the reform of the scientific research evaluation mechanism and the talent evaluation mechanism to prevent undesirable short-term effects. More outstanding talents should be permitted to excel. The autonomy of universities and research institutes should be expanded, and leading scientific research personnel should be endowed with greater decision-making power.

### 4.7 Establish a disruptive technology cultivation mechanism for the integration of production, education, research, and application

Disruptive technology requires a long-term cultivation process from discovery to maturity and industrial applications. Improvements in the disruptive technology cultivation mechanism that is enterprise-led and deeply integrated with production, education, research, and application are recommended. It is also recommended to establish a disruptive technology development fund to support potential disruptive technology research and reduce the risk of disruptive technological innovation in enterprises. With regard to disruptive technologies that are maturing, we should support industrialization with policies such as tax reduction and interest subsidy loans; thereby, we can provide an environment suitable for the development of disruptive technologies.

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