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Review

Opportunities and Directions for the Development of High-end New Materials Intelligent Manufacturing

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Abstract: High-end novel materials are the fundamental building blocks for big projects and high-end machinery, while intelligent manufacturing is a crucial route for the manufacturing sector to advance towards high-end development. To satisfy the demands of major equipment for high-end new materials and to improve the manufacturing level of high-end new materials, intelligent manufacturing must be deeply integrated with high-end new material manufacture. In addition to analyzing the features of high-end new materials in high-performance manufacturing, the overall integration and lightweight manufacturing of complex components, and the integration of high-end components with low-cost green manufacturing, this article delves deeply into the need for intelligent manufacturing for high-end new materials.

Simultaneously, a summary was provided of the difficulties that the conventional “trial-and-error” R&D methodology in the material production industry encountered. The essay examines the opportunities and changes resulting from data-driven intelligent manufacturing R&D models for high-end novel materials. It outlines the main technologies that require immediate development and their future trajectories, using the intelligent processing and shaping of materials as an example. In order to promote the upgrading and leapfrog development of the material industry, the article also suggests countermeasures and ideas for accelerating the development of high-end new material intelligent manufacturing from aspects like fostering interdisciplinary talent, building an innovation system, strengthening research on key technologies, and speeding up the transformation of achievements.

Keywords: intelligent manufacturing; high-end new materials; technological innovation; industrial upgrading

1. Introduction

High-end novel materials are now a crucial factor in encouraging the creation of major engineering projects and expensive equipment. Advanced basic materials like high-performance aluminum alloys, magnesium alloys, and titanium alloys, as well as critical strategic materials like superalloys and innovative new materials like additive manufacturing metals, are essential in critical strategic domains like energy, transportation, aviation, aerospace, electronic information, and weaponry (Xie et al 2020). With ongoing advancements in next-generation information technology, communication technology, biotechnology, and new energy technologies, the world is currently going through another round of technological revolution and industrial transformation. These advancements are speeding up the integration of these technologies with advanced manufacturing technologies. Unprecedented potential for the modernization, intelligence, and greening of the manufacturing sector have been brought about by this movement. China is actively taking advantage of this unique chance to advance intelligent manufacturing in industries including machinery manufacture, with notable outcomes. Overall, nevertheless, China’s intelligent manufacturing development is still in its early phases, particularly when it comes to the relatively new sector of intelligent production of novel materials (Zhong et al., 2020).

China is a significant material power, but it has a long way to go before it can be considered a powerful material power. China has made some progress in the sector of high-end novel materials manufacturing, but it still lags far behind other countries with more developed levels. China is subject to restrictions from other nations in areas like standards systems and new materials technology, as well as product monopolies, which restrict China’s ability to develop, use, and industrialize new materials in crucial fields. China’s progress in these areas has been hampered by its low

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technological level. China is currently going through a period of strategic change for high-quality development. A unique potential for the growth of China's new material industry is presented by the rapidly increasing demand for high-end new materials in industries such energy power, information display, transportation vehicles, and life health (Zhong et al., 2020). However, this also creates more demands for the production of important components and high-end novel materials. China urgently has to take the lead and aggressively develop intelligent manufacturing technologies for high-end novel materials, supporting the modernization and transformation of the materials industry, given that intelligent manufacturing is quickly becoming a global trend. This has to do with China's place in the global technology competition as well as the future growth of its industrial sector. The characteristics of high-end new materials manufacturing are first described in this article, which then examines the issues and difficulties faced by traditional R&D models, highlights the opportunities and changes brought about by the intelligent manufacturing R&D model for materials, and lists the essential common technologies that should be used for intelligent manufacturing of high-end new materials.

2. The manufacturing characteristics of high-end new materials

2.1. The integration, large-scale production, and lightweight manufacturing of complex components

Three key features in the realm of high-end novel material manufacturing are integration, large-scale, and lightweight manufacture. Using cutting-edge technologies like precision casting and additive manufacturing, integrated manufacturing combines several parts into a single unit, increasing structural strength, decreasing assembly errors, and lowering maintenance costs. The goal of large-scale manufacturing is to create components with greater volume and size. The development of large material preparation technologies, research into large processing equipment, and the use of sophisticated inspection techniques can all successfully solve the difficulties associated with material preparation, processing equipment, and quality inspection. By maximizing structural design and material selection, lightweight manufacturing lowers component weight while maintaining performance and increasing energy

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efficiency. Together, these three manufacturing traits provide a powerful catalyst for the development of contemporary industry by promoting the use and creation of cutting-edge novel materials in crucial domains including automotive, marine, and aerospace engineering (Sun et al., 2022).

2.2. Integrated manufacturing of materials, structures, and processes

The rapid advancement of additive manufacturing technology has brought about a new technological breakthrough in the processing and fabrication of big essential metal components for high-end equipment. During the manufacturing process, this technology produces special conditions. On the one hand, it effectively avoids common defects in traditional ingot metallurgy, like segregation, porosity, and coarse solidification structures, by using extraordinary metallurgical conditions, such as tiny melt pools at ultra-high temperatures and strong convection of the melt. However, non-equilibrium solidification conditions, like extremely high temperature gradients and extremely rapid cooling rates, offer plenty of room to overcome the alloying constraints of conventional ingot metallurgy and create a new class of complex superalloy materials with high performance (Wang, 2014). It is important to note that additive manufacturing may achieve accurate online control of alloy composition, microstructure, and performance during the point-by-point continuous melting and solidification deposition process. In the design and production of intricate parts like novel high-temperature alloys, the fusion of shape and function, and the processing and shaping of novel materials like gradient materials, this shows notable benefits over conventional methods.

2.3. Low-cost green manufacturing of high-end components

Its core competitiveness, which is a tangible representation of high added value and high social and economic advantages, includes low-cost and low-consumption production of high-end components in addition to the ongoing pursuit of high quality and high performance. Low consumption and green manufacturing of high-end new materials and their components have become an essential choice to promote the high-quality development of China’s economy and the realization of the “double carbon” goal. This is because the basic materials industry’s manufacturing technology, which uses a lot of energy and produces a lot of pollution, has become a bottleneck problem impeding social development in light of the increasingly serious energy and environmental crisis.

3. Problems and Challenges in the R&D Model of High-end New Materials

Precise control of the material manufacturing process is becoming more and more necessary due to the high demands for high-performance materials, the complexity and lightweight nature of components, and the efficiency and low cost of production. For a long time, research in the field of high-end novel material manufacture in China has been based on a task-based paradigm that is driven by requirements. This model is good at follow-up but not very good at basic theoretical research. It frequently uses an 'experience optimization' strategy, which is typified by simple repeated trial-and-error and experience accumulation. This leads to high randomness, lengthy development cycles, large prices, and low scientific rigor of novel materials. Internal metallurgical defects, dimensional deviations, and high residual stress are only a few of the persistent and pervasive problems that arise from inadequate and unsystematic research on material processing and preparation, as well as a lack of process control. In high-end manufacturing, the stability and consistency of new material products' quality have turned into a "bottleneck" problem.

4. The changes and opportunities brought by the smart manufacturing R&D model of three-end new materials

One of the most promising cutting-edge research directions in new material preparation and forming processing technologies in the early 21st century is intelligent material forming and processing technology, which has been progressively developing since the mid-1980s with the widespread use of computers, artificial intelligence, databases, and sophisticated control technologies (Wadley et al., 1998b). This technique combines feedback control of the preparation and forming processing process, real-time online monitoring, component design, and material microstructure performance design. In order to achieve the best material microstructure performance

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and forming processing quality, it aims to replace the “trial and error method” in traditional material preparation and processing with integrated design and intelligent process control methods. This will allow for precise control of the preparation and processing process as well as precise design of material microstructure performance. However, early research in intelligent technologies mostly used a technical approach based on physical modeling and expert systems using mathematical physical models and prior knowledge because of the limitations imposed by the technology level at the time. A new model of full-process correlation and parallelism has replaced the traditional sequential and iterative “trial-and-error” development model of materials in the last ten years due to the development and application of key technologies in materials genome engineering, which are characterized by efficient material computation, high-throughput experiments, and big data technology. This has completely accelerated the entire process of material discovery, development, production, and application, which in turn has encouraged the study and engineering application of new materials (Wang et al., 2020).

Materials gene engineering can be broadly classified into three sorts of working modes: data-driven, computation-driven, and experiment-driven (Agrawal et al., 2016). The fourth paradigm of material R&D, which is data-based and builds models using techniques from materials informatics, is one of them. The data-driven model suggests a new paradigm for material innovation. The efficiency of material R&D and the caliber of engineering applications can be greatly increased by using artificial intelligence, such as machine learning, to analyze complex relationships among multiple parameters. This could have disruptive effects and speed up the development of new materials (Xie et al., 2021). The creation of novel concepts and techniques for thorough optimization and intelligent control across the whole material manufacturing and processing process is made possible by data-driven models. The foundation and prerequisite for attaining intelligence is digitalization. Large volumes of simulation data for material production processes are currently available due to the quick development of technologies like Integrated Computational Materials Engineering (ICME) and effective computational simulations for materials. Simultaneously, a great deal of precise information about material processes and quality has been gathered due to the extensive use of intelligent perception technologies and real-time monitoring in the material manufacturing process. Real-time simulation and full-process digital modeling based on data models rather than conventional physical models are now feasible thanks to the development of data fusion and mining technologies and the revolutionary advances in artificial intelligence technologies like deep learning. Accordingly, integrating intelligent control technology is anticipated to address a number of issues in the material manufacturing process, such as intricate Multiphysics coupling, time-varying disruptions, inherent nonlinear interactions, and optimization that takes into account many variables and objectives.

Many developed industrial nations are actively exploring digital and intelligent manufacturing technologies for high-end components in the current climate of intense global technological competition. This is speeding up the shift from the conventional “trial-and-error” R&D model to an effective model of “digital simulation and intelligent control.” With their significant benefits in digitization and informatization, digital twins and virtual manufacturing technologies are being used more and more in real production. China must take advantage of the current development opportunities, concentrate its advantageous resources, and carry out in-depth research on the intelligent manufacturing R&D model of materials in the context of intelligent manufacturing if it hopes to catch up in this area and close the gap with other advanced nations. In order to achieve a leapfrog development in the field of high-end new material manufacturing process technology, it is important to actively introduce cutting-edge technologies like artificial intelligence and big data analysis, encourage the development of new principles and methods for data-driven material manufacturing, build an integrated manufacturing system that covers “component design - process optimization - process control,” and develop key technologies and processes for intelligent processing and forming.

Actively conduct research on intelligent manufacture of high-end novel materials, take advantage of development prospects with vigor, and lead discipline development. Intelligent manufacturing has emerged as the primary focus of global high-end manufacturing competition in the fourth industrial revolution wave, which is being driven by the broad use of artificial intelligence technology. This trend is unavoidable in the growth of advanced manufacturing in China. International study and application of intelligent control-based material processing and forming is still in its early stages at the moment. It will be very important for advancing disciplinary development and taking the lead in global disciplinary development if China can seize this unique development opportunity and carry out pertinent research on intelligent production of high-end novel materials.

Fearlessly utilizing state-of-the-art technologies like artificial intelligence, big data analysis, and integrated computational materials engineering to improve original innovation capabilities and create effective R&D models. The many difficulties of cross-scale correlations, interactions, and time-varying complexities of microstructure, defects, and performance in the material processing and forming process have become too much for the conventional “trial and error” research model based on experience, experiments, and numerical simulations. Therefore, the secret to overcoming the bottleneck of advanced new material manufacturing technology is the thorough application of big data analysis, artificial intelligence, integrated computational materials engineering, and other cutting-edge research technologies to create effective R&D models and improve original innovation capabilities.

Make every effort to develop new concepts and techniques for the thorough optimization and accurate control of the material and component processing and shaping processes, as well as to break through key technologies in the intelligent manufacturing of high-end new materials. This will provide strong support for the material industry’s advancement and leapfrog development. Achieve high-quality manufacturing, meet the urgent national demand for high-end key materials, promote the upgrading of the materials industry, and realize high-quality development by resolving bottleneck issues like the many influencing factors in material processing, complex multi-physical field coupling and multi-objective parameter interactions, and the evolution of organizational structure and defects throughout the entire process.

Lead the development trend in the field of materials processing engineering, actively support the deep interdisciplinary integration of materials processing, virtual manufacturing, artificial intelligence, and other disciplines, and create theories and techniques for digital modeling and intelligent control throughout the materials processing process.

5. The development direction of common key technologies for high-end new materials intelligent manufacturing

The integration of artificial intelligence with manufacturing technology, the breakthrough of common key technologies in intelligent material manufacturing, and the creation of an intelligent manufacturing system that spans the entire lifecycle, full process, and multiple scales are currently the main areas of development in high-end new materials intelligent manufacturing. “Materials must become parts; parts must become tools.” High-end novel material manufacturing relies heavily on material forming and processing. Casting, forging, additive manufacturing, welding, heat treatment, semi-solid forming, powder injection molding, and so forth are some of the subfields of smart technology research that are currently underway. Using the technology of intelligent material shaping and processing as an example.

Materials fundamental database and database technology geared towards engineering applications are the common key technologies of intelligent materials manufacturing that urgently need to be developed.

Intelligent design technology that uses artificial intelligence, sophisticated databases, and computational integration to integrate the forming process and material performance

Intelligent perception technology and online detection for material structure, performance, and process parameters during the material forming process

Technology for prediction and control of the whole material processing and shaping process

Material-specific intelligent forming systems that enable interactive and cooperative development and control of the complete intelligent forming process.

6. Conclusion

Through an analysis of its features in areas including integrated production, low-cost green manufacturing, and the lightweighting of complicated components, this paper delves deeply into the development potential and directions for intelligent manufacturing of high-end novel materials. Additionally, it highlights the drawbacks of the conventional “trial and error” approach to research and development. Based on this, the essay highlights the substantial benefits of a data-driven intelligent manufacturing R&D model in terms of increasing R&D efficiency and attaining precise control, and it goes into detail about the changes and opportunities that this model brings.

The paper also discusses the common essential technologies—such as intelligent design, online testing, and intelligent perception—that are urgently required for the intelligent manufacture of high-end novel materials. The findings of this study offer theoretical justification and useful recommendations for the modernization and rapid advancement of China’s material sector.

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