



Characterization of Advanced Materials for Smart Manufacturing: A Review

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Abstract

The application of big data processing, artificial intelligence, and advanced robotics technology, as well as their interconnectivity, to improve industrial performance and optimize energy consumption, is known as smart manufacturing. Analysing advanced materials' characteristics and behaviours to optimize their performance in manufacturing processes is part of defining them for smart manufacturing. For materials to be developed that can react, adjust, or self-optimize in real-time during production, this characterization is essential. In this paper, the idea of "advanced materials for smart manufacturing" is defined, its characteristics are discussed, its current implementation status is stated, the difference between the current manufacturing system and the anticipated future smart manufacturing system is analysed, and the related technologies and their contributions to smart manufacturing technology are discussed. Additionally, important methods and elements of the characterization of innovative materials for smart manufacturing were discussed, along with potential, implementation issues, and future directions. To guarantee that materials satisfy the demanding requirements of contemporary production settings, characterization of new materials for smart manufacturing necessitates the use of an extensive range of methodologies. Through the application of these characterisation techniques, producers can create and employ materials that improve productivity, effectiveness, and creativity in intelligent manufacturing systems.

Keywords: Smart manufacturing, Advanced materials, Electron microscopy.

1.1 Introduction

Advance materials, also known as intelligent or responsive materials, have the ability to adapt dynamically to external stimuli like as temperature, pressure, magnetic and electrical fields, and chemical conditions. These responses frequently cause substantial changes in the properties of a material, such as form, stiffness, viscosity, and optical features. Smart materials can conduct self-regulation, self-healing, or self-adapting capabilities, making them crucial to sophisticated engineering and technological applications [1]. Additional terminologies for advanced materials include nanomaterials, smart materials, engineered materials, specialty materials, and high-performance materials. In the process of developing, creating, and producing products and materials, advanced materials characterization is an essential method. The methods employed make it possible to accurately and thoroughly characterize materials, which in turn makes it possible to enhance their qualities and create more sophisticated materials. In business, research, and construction, advanced materials characterization is crucial, and its application is still vital to the creation of more durable and sophisticated goods and materials [2].

Advanced materials encompass a wide range of materials, including smart materials like shape memory alloys and materials that have been altered at the nanoscale, as well as advanced metals, ceramics, polymers, and composites. This book examines the vast array of sophisticated materials utilized in the manufacturing sector and speculates about their potential future developments [3]. From alloys of metals and ceramics to the newest polymers, experts are continuously advancing and looking for new, cutting-edge materials to use in production. Advanced materials possess unique properties that surpass the capabilities of conventional industrial materials, regardless of their specific attributes like durability, toughness, or elasticity [4]. For instance, lightweight materials enable manufacturers to lower the weight of automobiles, airplanes, and other modes of transportation, which is vital to the decarbonization of the economy [5]. sophisticated materials for smart manufacturing can take many various forms, ranging from the newest sophisticated ceramics to metal alloys. Modern materials might be more resilient than their traditional equivalents and save the producer money on upkeep. They are used in many different industries, including as the automotive, aerospace, defence, and power generation industries. Advanced materials provide unique technical purposes due to their properties [6].

The process of examining and comprehending a material's chemical, electrical, as well as physical characteristics is known as characterization. It is a crucial component of materials engineering analysis that aids in determining which material is best for a certain application [7]. Advanced material characterization methods are used to analyse a wide range of characteristics, including as mechanical strength, thermal stability, electrical conductivity, and corrosion resistance. Engineers can improve their designs for greater reliability and efficiency and develop a better understanding of the material characteristics of various elements by employing these strategies. It also helps them to create new materials with distinct behaviours according to the products they are meant to be used for, making them safer and more efficient [8].

1.2 Importance of Advanced Materials

Because they offer special qualities that can be adapted to certain uses, advanced materials are significant. These characteristics can aid in enhancing durability, lowering weight, increasing performance, and increasing efficiency. Globally increasing popularity of portable electronics and electric cars encourages the development of energy storage devices, like batteries and supercapacitors, toward higher power and energy densities. However, the development of new materials for these devices is crucial to their continued development [9]. Numerous industries, including aerospace, automotive, electronics, healthcare, and energy, have developed significantly because of advances in advanced materials. They have been employed, for instance, to create biocompatible materials for medical implants, flexible and high-capacity batteries for portable gadgets, and lightweight and robust composite materials for cars and airplanes [10].

Addressing global issues like sustainability, climate change, and energy security also requires research and development in advanced materials. We can produce more effective and sustainable technology, lessen waste, and enhance people's quality of life overall by creating innovative materials with better qualities [11]. This essay provides a comprehensive overview of advanced materials, discussing their varieties, benefits, drawbacks, and uses. Furthermore, the prospects and future trends in the development of innovative materials are emphasized [12].

2. 1. Types of advanced Materials:

Based on how they respond to different types of environmental stimuli and how they behave, advanced materials can be categorized. Advanced polymers, composites, nanomaterials, and advanced alloys are a few popular categories of advanced materials [13].

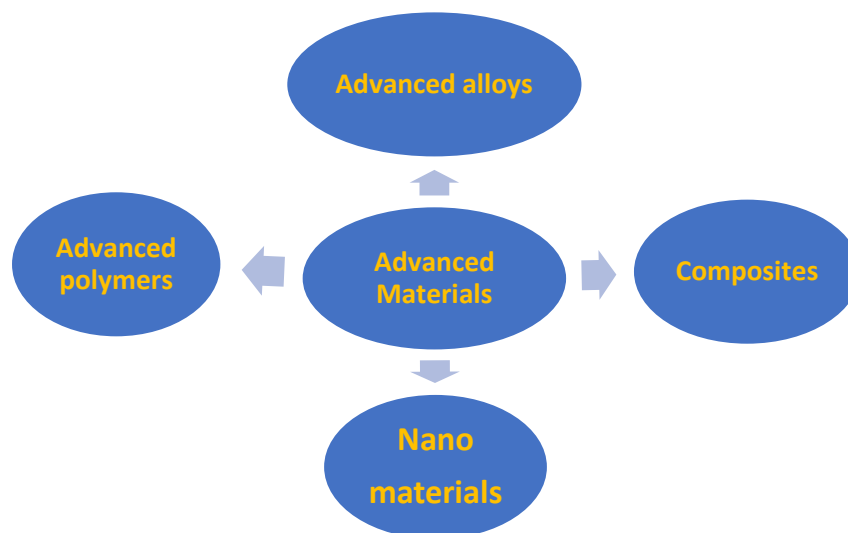
2.1.1 Advanced alloys: The metallic materials known as "advanced alloys" are made expressly to withstand the severe requirements of astronautical and space engineering. Superior mechanical qualities, resistance to corrosion, resistance to high temperatures, and exceptional thermal stability are all designed into these alloys [14][15].

2.1.2 Advanced polymers: Innovative materials with specific chemical structures and characteristics that provide excellent performance, adaptability, and reliability in a range of applications are known as advanced polymers. A matrix material, or polymer, which is typically low-strength and low-modulus, and a fiber, which is comparatively high-strength and high-modulus, can be combined to form them. Strength, durability, and other qualities can be enhanced with advanced polymers [16]. during instance, comparable polymers are used to make replacement lenses during cataract surgery. The two main materials that make up an advanced polymer composite are the polymer, or matrix material, which is typically the low-strength and low-modulus component, and the fiber, which is the relatively high-strength and high-modulus component [17].

2.1.3 Composites: In their most basic form, composites are made up of two or more constituent materials that have distinct chemical or physical properties. They combine to form a material that has distinct properties from what they had alone. The matrix and fiber are a composite's two major parts. The foundation material is called the matrix, and the material is reinforced by the fiber [18]. Composites can use core materials,

fillers, additives, and surface treatments in addition to fiber reinforcements and matrix to offer special performance characteristics. (For instance, macroscopic, hybrid, fiber- and particle-reinforced materials) In comparison to conventional engineering materials, composite materials often have higher strength- and modulus-to-weight ratios. These features have the potential to reduce a system's weight by up to 20–30%. Reducing weight leads to either enhanced performance or reduced energy consumption. Advanced composites feature excellent damping qualities, a high creep resistance, and favourable dynamic properties. It is indeed possible to rebuild metallic airframes with fatigue damage using composite materials because of their higher fatigue performance [19].

- 2.1.4 Nanomaterials: A group of materials referred to as nanomaterials is made up of discrete units having at least one dimension smaller than 100 nano meters. They are sometimes divided into three categories: organic (carbon-based), inorganic (non-carbon-based), and hybrid (combining the two) materials. They can be composed of any element [20]. Nanomaterials can be patterned patterns affixed to a surface or discrete structures such as nanoparticles or nanotubes. Because of the special qualities that appear at the nano meter scale, nanomaterials have garnered a lot of attention from researchers. These characteristics include various interactions with light, distinct surface textures, and large surface area for chemical reactions. The specific way that nanomaterials behave is dependent upon the specific material [21]. As the area has developed, nanomaterials have become more significant because research technology has made it possible to investigate materials at the nanoscale with ever-increasing precision. The range of nanomaterials available today has expanded due to advances in scientists' comprehension of synthesis methods [22].



2.2 Importance of materials characterization

It is possible to analyse a broad range of attributes, including mechanical strength, thermal stability, electrical conductivity, and corrosion resistance, using advanced material characterization techniques. Understanding the material properties of various system components allows engineers to optimize their designs for increased performance and dependability [23].

The several approaches to material characterization will be covered in this section.

2.2.1 Electron microscopy: In this method, the structure and composition of materials are examined at a very tiny scale using an electron microscope. Materials' uniformity, purity, and structure are assessed by

electron microscopy[24].

2.2.2 X-ray diffraction analysis: This method examines the crystalline structure of materials by using X-rays. The structure, content, and characteristics of materials as well as many factors can be accessed via X-ray diffraction [25][26].

2.2.3 Spectroscopy analysis: Spectroscopy is a technique that analyses the interaction of light with materials. There are different types of spectroscopies, such as Raman spectroscopy, infrared spectroscopy, and optical absorption spectroscopy [27][28].

2.2.4 Thermogravimetric analysis: Thermogravimetric analysis is a technique that measures variations in the weight of materials as they are subjected to temperature changes. This technique is used to evaluate the thermal stability and resistance to thermal degradation of materials [29][30][31].

3. Advantages and disadvantages of materials characterization

3.1 Advantages: For both industry and research, advanced materials characterization has a number of significant benefits. State-of-the-art characterisation techniques have enabled some of the most significant technical achievements [32]. Better knowledge of the composition and structure of materials, enhanced material selection and property optimization, creation of more resilient, long-lasting, and effective materials, and discovery of novel applications and uses for currently available materials are some of the most significant advantages [33].

3.2 Disadvantages:

Each approach has its bounds. It is critical to select the right procedure for the job and the particulars of the material under consideration. Many have high equipment and material costs, which can restrict their use and accessibility for labs and businesses on a tight budget. Certain methods could take a while to analyse, which could make them less effective in situations where quick material evaluation is needed. The process of interpreting the collected data can be difficult and call for certain training and expertise [34].

4. Advanced Materials Applications

Because precise understanding of material characteristics and behaviours is essential to producing products that are efficient, safe, and long-lasting, advanced material characterisation has a significant impact on product design and manufacturing. By using these specialized methodologies, it also allows designers and manufacturers to enhance the optimization of the product's design and production process [35].

Modern advanced materials have characteristics that beyond those of common materials like titanium, steel, and aluminium to achieve unprecedented performance, providing previously unimagined uses. Advanced metal alloys are essential to modern medicine, gas turbines, the oil and gas sector, and composite materials have already completely changed the transportation industry. Advanced materials give engineers new functionalities as well as prospective ways to reduce environmental effect of manufacturing, increase sustainability, and conserve resources[36]. In addition to metals, composites,

polymers, and ceramics, advanced materials and alloys increasingly comprise organic materials and methods for manipulating them at the cellular level. For instance, materials with unique properties that can affect physical, chemical, and biological behaviour at a scale of one to 100 nano meters can now be manipulated thanks to nanotechnology. Innovation in health will undoubtedly be impacted using modern materials at this microscopic scale, but it will also spur the development of new consumer goods, energy systems, and innovative manufacturing methods [37].

The automotive sector has benefited from enhanced fuel efficiency and vehicle safety due to the development of lighter and stronger materials made possible by sophisticated materials characterization. This technique is applied in the construction sector to assess the strength and quality of building materials like steel and concrete. The qualities of materials used in the production of electronic devices, such as integrated circuits and semiconductors, are assessed in the electronics industry through the study of materials [38].

6. Conclusion & Prospects and Challenges

Production techniques, print-on-demand technology, developing quantum computers, data collection and analysis, and the use of AI in design, monitoring, and problem-solving are all examples of how businesses are becoming more and more widespread and capable. We already rely somewhat on sophisticated materials for industrial applications in our working life, whether we even recognize it.

Modern manufacturing and materials can close that gap. Another idea that is starting to gain traction in the market is the creation of sophisticated biomaterials and proteins in the lab for human consumption, such as 3D-printed meats. New sophisticated biomaterials, inorganic advanced materials, and small, AI-powered smart devices will work together to develop a new class of prostheses that can replace body parts. They will enable amputees to function nearly perfectly, if not more so.

New supercapacitor technology for storing intermittent renewable energy and microscopic materials that can change their shape to store data in computer memory are predicted to be developed in the future thanks to improved materials. Additionally, the development of new and improved additive manufacturing (3D printing) technologies is heavily reliant on advanced metals, ceramics, and composites. Artificial intelligence is also being utilized to refine and produce new forms of corrosion-resistant alloy.

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