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Green manufacturing represents a pivotal shift in industrial practices, aimed at harmonizing economic growth with environmental stewardship. This chapter delves into the core principles and drivers behind green manufacturing, exploring how they collectively foster a more sustainable industrial ecosystem. At its essence, green manufacturing seeks to minimize the environmental impact of production processes while enhancing resource efficiency. The principles underpinning this approach are grounded in reducing waste, conserving energy, and utilizing environmentally friendly materials. By embedding these principles into the core of manufacturing practices, industries can significantly reduce their carbon footprint and contribute to broader sustainability goals.Central to green manufacturing is the efficient use of resources. This principle emphasizes minimizing the consumption of raw materials, energy, and water throughout the production process. Strategies such as process optimization, material substitution, and closed-loop systems are employed to achieve this goal.

This chapter touches upon the incorporation of such computational intelligence in the context of sustainable manufacturing of advanced materials from both present context and future prospect. The material creation framework depends on fundamental ideas, tools and techniques for producing sustainable materials and ecologically designed and assessed materials. The computational intelligence is studied and has shown significant importance in optimization of manufacturing process and also improvement of material properties of parts. It empirically provides pragmatic insights about the advantages and hurdle of the success of applications based on empirical studies of the success of the application on many industries. It ends by discussing economic, technologic and regulatory barriers to wide spread delivery and strategies to overcome these barriers and to continue innovation in sustainable manufacturing.

The advent of new materials offers promising solutions for enhancing energy storage systems, improving energy efficiency, and mitigating environmental impacts. These advanced materials are characterized by their unique properties, which enable them to address the limitations of conventional materials and contribute to innovative technologies in various fields. In the realm of renewable energy, emerging materials are transforming photovoltaic technology. Traditional silicon-based solar cells are being complemented by new materials such as perovskite solar cells, organic photovoltaics, and quantum dots. Perovskite materials, known for their exceptional light absorption and charge transport properties, have demonstrated the potential for high-efficiency, low-cost solar cells with ease of fabrication. Organic photovoltaics, which use organic compounds to convert sunlight into electricity, offer flexibility and lightweight characteristics, making them suitable for a range of applications from wearable electronics to building-integrated photovoltaics.

Bio-based materials are those materials which are taken either wholly or partly from bio-based materials, e.g., plants & microorganisms. These materials can be distinguished by their renewability & some measure of carbon capture during their growth. They are gradually becoming famous as a viable option to existing materials because of heightened consciousness about environmental issues. Polymers, coatings, and composites are discussed as an extensive class of bio-based products; these materials possess several characteristics, including biodegradability & non-toxicity. Thus, bio-based materials have been practiced in different industries & areas. Most of these materials substitute fossil-based resources & consequently, processes used in manufacture of these materials contribute to lowering of carbon footprints. Bio-based & biodegradability are two important concepts for waste management & circular economy. In conclusion, applications of bio-based materials can energize sustainable growth, minimize carbon impressions, aid progress, & establish sustainable economies.

Metallic NPs, particularly (AuNPs), have attracted great attention due to their unique characteristics and applications. NPs have unique surface qualities as compared to bulk substances, including diagnostics and medicine administration. Therapeutic plant extracts exhibit stability, making them suitable for various applications as a result of their biocompatibility and flexibility, thereby minimizing their phytochemical properties. The biogenic NPs were characterized using UV-vis, FTIR, and SEM, demonstrating antibacterial activity and potential for large-scale synthesis. Green synthesis technique adopted ecological acceptable practices and showed the promise of plant-based synthesis in biomedical applications. Phytoextract is cost-effective and eco-friendly method for producing AuNPs, outperforming conventional chemical synthesis methods. Along with providing workable substitute for chemical synthesis in pharmaceutical, medical, and agricultural domains, it also demonstrates the viability of green synthesis for the production of bioactive AuNPs and shows it prospective applications.

In recent years, there has been a growing demand for development of eco-friendly material for long-lasting, lightweight, superior strength and fire retardant. This drawn the researchers to use various natural fiber as a reinforcing agent in a matrix material. The use of bio-fibers as reinforcement in place of synthetic fibers (carbon and glass fiber) in the creation of polymer matrix composites has garnered a lot of interest in the last few years. Several natural fibers have been exploited as reinforcing materials by researchers in the past. Excellent adhesion to various materials, high strength, toughness, resistance to chemical assault, humidity, and moisture resistance, superior electrical insulating properties, odorlessness, non-toxicity, and minimal shrinking are only a few of the qualities of epoxy resin to be used a matrix material. Information regarding environmentally acceptable materials that can be used in high-temperature applications is needed by numerous sectors.

The demand for sustainable energy storage has driven advancements in material science, where Computational Intelligence (CI) is emerging as a key tool. CI techniques like machine learning and neural networks optimize complex processes, enhancing material properties and manufacturing efficiency. In energy storage, CI accelerates the discovery of materials for advanced batteries, supercapacitors, and hydrogen storage, improving energy density, cycle life, and safety. CI also aids environmental applications, such as water purification and carbon capture, by enhancing material performance. Despite challenges like data availability and computational resources, CI's integration into manufacturing promises a more sustainable future.

The chapter studies the use of AI-driven optimization to apply methods of sustainable manufacturing based on the scenario of eco-efficient production of advanced materials. It also shows how AI methods could be used, including machine learning and optimization algorithms, to increase the efficiency of manufacturing processing flows while decreasing environmental impact. The chapter covers a scope of AI-based predictive maintenance, process optimization, and resource management strategies that result in a reduction in waste generation, energy use, and gases emitted. These are demonstrated in practice through case studies and examples in the manufacturing of advanced materials, ensuring the transformation of conventional manufacturing practices into more sustainable operations. In fact, the implementation of AI into the practice of manufacturing that recognizes and promotes sustainable manufacturing would massively contribute to the enhancement of full sustainability benefits by encouraging environmental stewardship while fostering innovation in material science.

The chapter is focused on integrating machine learning and computational intelligence into green manufacturing processes. ML and CI offer data-driven solutions toward industries strive for reduced environmental impacts through resource usage, energy consumption, and waste reduction, among others. This chapter will focus on some very prominent algorithms, such as neural networks, reinforcement learning, and fuzzy logic, and their applications in predictive maintenance, process optimization, and supply chain management for sustainability. The chapter relates the integration of ML and CI in achieving eco-friendly manufacturing goals—reduction of carbon footprint and improvement in operational efficiency—through case studies and practical examples. It discusses the role played by digital twins, IoT

Abrasive Jet Machining is a non-traditional machining process with the considerable versatility of use, mostly in cutting, cleaning, and deburring hard and brittle materials. In AJM, optimal parameters involve such things as abrasive flow rate, pressure, and standoff distance, all of which are very important for attaining the appropriate performance metrics with respect to material removal rate (MRR) and surface finish. It applies evolutionary algorithms, specifically Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), to the optimization of AJM processes. The evolutionary algorithms may efficiently locate optimal parameter combinations from computer simulations of various machining conditions into significant reductions in energy, wear, and increases in accuracy in machining. The computational approach given below provides a robust framework for achieving precision in AJM, beating traditional optimization techniques. Experimental verification has demonstrated the effectiveness of proposed EA-based models in optimizing efficiency in AJM.

The roll forming of Advanced High Strength Steels (AHSS) is characterized by several challenges, mainly because of their specific mechanical properties: springback, tool wear, material fracture, and lubrication inefficiencies. This chapter presents an optimized manufacturing process using MOGAs, balancing opposing objectives like low springback and tool life by utilizing MOGAs. The study examines the impact of advanced tooling materials, coatings, finite element analysis process simulations, and lubrication techniques on joint effect. Case studies demonstrate successful application of solutions, resulting in higher quality products, reduced costs, and improved operational efficiency. The proposed approach will enhance the durability and strength-to-weight ratio of AHSS, thereby overcoming the limitations of the cold roll forming technique, thereby enabling its wider industrial applications in automotive and construction sectors.

Artificial intelligence and deep learning technologies are driving transformations in material science, particularly in predicting material property through machine learning applications. In this chapter, we are concerned about how materials property prediction can be revolutionized by advances in new state-of-the-art technologies enabling more accurate and efficient predictions in comparison to the traditional methods which incur time-consuming and cost-consuming expense. While both ML and deep learning offer powerful alternatives, they require large datasets and robust algorithms to accurately map complex interplay between the material structure and its properties. In this text you will read about employing deep learning architectures, such as CNNs and RNNs, in predicting properties such as mechanical strength, thermal conductivity and electronic behavior. The chapter discusses successful case studies and predicts future material science research and industry practices integrating AI-driven approaches.

Mathematical modeling and computational methods are the critical techniques necessary to meet such complex challenges in the scope of a broad range of emerging engineering fields. This chapter emphasizes how these techniques might be dovetailed for applications of handling real problems within renewable energy, biomedical engineering, autonomous systems, and smart infrastructure. Powerful algorithms, numerical methods, and data-driven models may be used to simulate, predict, and even optimize system behavior under various conditions. The synergy between mathematical theories and computational tools is highlighted: artificial intelligence, machine learning, and high-performance computing, which improve design efficiency and bring innovation. A set of practical benefits presented in case studies of modern engineering applications benefits from these approaches. The chapter puts theories together with practice in giving an all-round overview of how computational methods drive advancement in engineering.

The selection of optimal materials for composite structures is an important step in engineering design, balancing performance, cost, and weight. In this chapter, the Artificial Bee Colony (ABC) algorithm, a nature-inspired optimization technique, is applied to efficiently identify the best composite material configurations. The ABC algorithm is inspired by the foraging behavior of honeybees, offering robust search capabilities and convergence properties. We discuss the principles underlying the ABC algorithm, its application to material selection, and performance evaluation criteria for composites. We compare it with traditional optimization techniques and make it clear that it outperforms them in solving complicated multidimensional problems. Case studies give an example of how it can be used for obtaining the optimal solution in several engineering applications. This chapter provides a comprehensive guide for researchers and engineers to improve design efficiency and performance by utilizing bio-inspired algorithms in material selection.

This chapter introduces machine learning (ML) in friction stir welding (FSW), a solid-state welding process that has gained significant attention in research and application. The chapter discusses five primary ML methods: artificial neural networks (ANNs), support vector machines (SVM), random forests (RF), particle swarm optimisation (PSO), and convolutional neural networks (CNNs). The chapter emphasizes the successful application of ANNs in optimizing FSW process parameters and predicting tool wear, tensile failure, and fracture positions. CNNs are shown to be effective for microstructure studies and image detection, while SVM is a good tool for FSW process monitoring and temperature control. RF is demonstrated to have good abilities in investigating welding defects and tool monitoring, while PSO is frequently used in FSW welding bead studies. The chapter provides a straightforward methodology for those interested in utilising ML in welding studies, particularly for FSW.

The realm of manufacturing is shifting towards intelligent manufacturing systems, emphasizing Industry 4.0, and integrating digital and physical environments using IoT, cloud systems, data analysis, and Machine Learning (ML). Smart devices and sensors gather data for various applications, which are then transmitted to the cloud for analysis. Cloud systems, powered by AI and ML, provide valuable insights. The latest inventory management technology uses automation and robotics for real-time monitoring, while MEMS are miniature sensors that detect changes. The text below discusses the diverse applications of IoT sensors such as accelerometers, microphones, gyroscopes, inkjet printer heads, and blood pressure sensors. The text discusses how IoT has revolutionized healthcare, agriculture, smart cities, manufacturing, retail, logistics, and energy. It highlights the role of IoT sensors in real-time monitoring, disease management, crop yield maximization, and enhanced safety measures. When integrated with intelligent manufacturing, it improves efficiency, safety, and sustainability.

The integration of machine learning with industrial automation is transforming the landscape of predictive maintenance, a critical aspect of modern manufacturing and industrial operations. This research explores the synergies between machine learning algorithms and industrial automation systems. Predictive maintenance leverages data-driven insights to anticipate equipment failures, thereby reducing downtime, optimizing maintenance schedules, and enhancing operational efficiency. The core of the research focuses on the application of machine learning techniques to predictive maintenance. The paper outlines the processes of data collection, feature extraction, model training, and validation, highlighting the challenges and solutions associated with each step. The work discusses industrial applications based on machine learning for predictive maintenance. Issues like data integration, scalability and security are discussed along with strategies to overcome the challenges.

This chapter explores the emerging innovations in Device-to-Device (D2D) communication aimed at optimizing the performance and efficiency of mechanical tools. D2D communication allows mechanical

resistance to compression and corrosion, chemical stability, strength etc. This review broadly discusses biomaterials, their classification into ceramics, metals and polymers, their characteristics, current applications, properties which are vital for in-vivo material action prediction. A bibliometric analysis was done which identified information gaps like prolonged in-vivo studies, extensive interdisciplinary research and highlighted the future scope of biomaterials in healthcare and medicine for development of composite materials, bioprinting, AI and personalized medicine.

Composite oxides have been proved to be valuable materials in optoelectronic applications. The combination of indium oxide and gallium oxide and other oxides can lead to enhanced optical and electronic properties, making them suitable for a variety of optoelectronic devices. A favorable energy band gap is needed in the visible region of the spectrum, indicating the applicability in optoelectronic devices such as LEDs and solar cells. Overall band gap engineering and tuning the radiative recombination is a challenge for new age semiconductors. Artificial Intelligence and Machine Learning have become powerful tools in the theoretical study and discovery of oxide materials for LEDs. By analyzing vast datasets, models can predict material properties, optimize synthesis parameters, and even generate new compounds with desired characteristics. This data-driven approach accelerates the material discovery process and enhances the precision of theoretical predictions, allowing researchers to explore a broader chemical space and identify optimal candidates for visible range light emission.

Chapter 3

Emerging Materials for Energy Storage and Environmental Applications

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ABSTRACT

The advent of new materials offers promising solutions for enhancing energy storage systems, improving energy efficiency, and mitigating environmental impacts. These advanced materials are characterized by their unique properties, which enable them to address the limitations of conventional materials and contribute to innovative technologies in various fields. In the realm of renewable energy, emerging materials are transforming photovoltaic technology. Traditional silicon-based solar cells are being complemented by new materials such as perovskite solar cells, organic photovoltaics, and quantum dots. Perovskite materials, known for their exceptional light absorption and charge transport properties, have demonstrated the potential for high-efficiency, low-cost solar cells with ease of fabrication. Organic photovoltaics, which use organic compounds to convert sunlight into electricity, offer flexibility and lightweight characteristics, making them suitable for a range of applications from wearable electronics to building-integrated photovoltaics.

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INTRODUCTION TO EMERGING MATERIALS FOR ENERGY STORAGE AND ENVIRONMENTAL APPLICATIONS

The advent of new materials offers promising solutions for enhancing energy storage systems, improving energy efficiency, and mitigating environmental impacts. These advanced materials are characterized by their unique properties, which enable them to address the limitations of conventional materials and contribute to innovative technologies in various fields. In the realm of renewable energy, emerging materials are transforming photovoltaic technology. Traditional silicon-based solar cells are being complemented by new materials such as perovskite solar cells, organic photovoltaics, and quantum dots. Perovskite materials, known for their exceptional light absorption and charge transport properties, have demonstrated the potential for high-efficiency, low-cost solar cells with ease of fabrication. Organic photovoltaics, which use organic compounds to convert sunlight into electricity, offer flexibility and lightweight characteristics, making them suitable for a range of applications from wearable electronics to building-integrated photovoltaics. Quantum dots, with their tunable bandgaps, enable the development of highly efficient solar cells that can capture a broader spectrum of sunlight. The pursuit of sustainable energy solutions has also spurred innovation in energy harvesting materials. These materials are designed to capture and convert ambient energy sources—such as solar, wind, thermal, and mechanical energy—into usable electrical power. Emerging materials for energy harvesting include thermoelectric materials, piezoelectric materials, and triboelectric nanogenerators. Thermoelectric materials, which convert temperature differences into electrical voltage, are being improved with materials like skutterudites and half-Heusler alloys to enhance efficiency. Piezoelectric materials, such as certain ceramics and polymers, generate electricity from mechanical stress and are used in applications ranging from self-powered sensors to energy-harvesting devices. Triboelectric nanogenerators exploit the contact electrification effect to convert mechanical energy into electrical energy, with applications in wearable devices and low-power electronics.

Environmental Remediation Materials: In addressing environmental challenges, emerging materials play a crucial role in pollution control and environmental remediation. Nanomaterials, including nanocapsules, nanofibers, and nanoparticles, are being utilized for their high surface area-to-volume ratio and reactivity to target and remove contaminants from air, water, and soil. For instance, magnetic nanoparticles are employed in water treatment processes to remove heavy metals and organic pollutants through magnetic separation (Kumar, R., et al., 2024). Photocatalytic materials, such as titanium dioxide and graphitic carbon nitride, can degrade organic pollutants under light irradiation, offering an effective method for water purification and air purification. Additionally, advanced sorbents, including biochar and engineered activated carbon, are used to capture and immobilize pollutants, enhancing the efficiency of soil and water remediation efforts.

Smart Materials for Environmental Monitoring: Emerging smart materials with sensing and responsive capabilities are enhancing environmental monitoring and management. These materials include responsive polymers, nanosensors, and smart coatings that can detect and react to environmental changes such as pollution levels, temperature variations, and humidity. Responsive polymers change their properties in response to environmental stimuli, providing real-time feedback on pollution levels or hazardous conditions. Nanosensors offer high sensitivity and specificity for detecting trace contaminants and environmental pollutants. Smart coatings, which can change color or exhibit other visual indicators in response to environmental changes, are being used for monitoring infrastructure health and environmental conditions.