Arabian Journal of Chemistry (2023) **16**, 105173

King Saud University

Arabian Journal of Chemistry

www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

Exploring the potential of nano technology: A assessment of nano-scale multi-layered-composite coatings for cutting tool performance

S. Ganeshkumar [a], **Amit Kumar** [a], **J. Maniraj** [b], **Y. Suresh Babu** [a], **Alok Kumar Ansu** [c], **Ashish Goyal** [c,*], **Iman Kareem Kadhim** [d], **Kuldeep K. Saxena** [e], **Chander Prakash** [f], **Reem Altuijri** [g], **M. Ijaz Khan** [h,i,*], **Ahmed M Hassan** [j]

[a] *Department of Mechanical Engineering, Sri Eshwar College of Engineering, Coimbatore 641202, Tamil Nadu, India*
[b] *Department of Mechanical Engineering, KIT-KalaignarKarunanidhi Institute of Technology, Coimbatore, Tamil Nadu, India*
[c] *Department of Mechanical Engineering, Manipal University Jaipur, Jaipur, Rajasthan 303007, India*
[d] *Pharmacy Department, Al-Mustaqbal University College, 51001 Hillah, Babil, Iraq*
[e] *Division of Research and Development, Lovely Professional University, Phagwara, India*
[f] *Department of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab, India*
[g] *Department of Physics, College of Science, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia*
[h] *Department of Mathematics and Statistics, Riphah International University, I-14, Islamabad 44000, Pakistan*
[i] *Department of Mechanical Engineering, Lebanese American University, Kraytem, Beirut 1102-2801, Lebanon*
[j] *Faculty of Engineering, Future University in Egypt, Egypt*

Received 3 May 2023; accepted 14 July 2023
Available online 20 July 2023

KEYWORDS

Nanotechnology coatings;
Nano-scale topography;
Nano-scale multi-layered-composite coatings;
Machining productivity;
Tool life;
Cutting forces;
Wear

Abstract Nano-scale Multi-layered Composite Coatings (Nano scale MLCC) offer potential benefits for cutting tool performance. Such coatings can be designed to improve tool durability and cutting efficiency by providing additional wear protection and improved heat dissipation. The Nano coatings can also be tailored to reduce friction, which can enhance productivity and reduce tool wear. The unique Nano-scale topography of MLCC helps to reduce the contact area between the cutting tool and the workpiece, thus reducing friction and heat. The coatings also include specific additive components that enhance the properties of the coating, such as corrosion resistance, lubricant retention, and improved thermal stability.This critical review explores the potential of Nano-scale multi-layered-composite coatings for improving the performance of cutting tools. The literature in this field is reviewed and discussed with respect to the performance benefits and challenges associated with the implementation of these nanotechnology coatings. The latest progress in nanofabrication, nanomaterials, and other technologies are discussed in relation to their ability to provide new and improved cutting tool applications. The review summarizes the current state

---

[*] Corresponding authors at: Department of Mathematics and Statistics, Riphah International University, I-14, Islamabad 44000, Pakistan (M. Ijaz Khan); Department of Mechanical Engineering, Manipal University Jaipur, Jaipur, Rajasthan 303007, India (Alok Kumar Ansu).
E-mail addresses: ashish.goyal@jaipur.manipal.edu (A. Goyal), scientificresearchglobe@gmail.com (M. Ijaz Khan).

https://doi.org/10.1016/j.arabjc.2023.105173
1878-5352

of the art on Nano-scale multi-layered-composite coatings and their influence on cutting tool performance, with particular focus on machining productivity, tool life, cutting forces and wear rates. Recommendations are provided on which Nano-scale coatings may best fit the demands of particular machining operations, and on future research directions in this field. The review also discusses the challenges and future advancements of Nano-scale coatings and other methods for improving cutting tool performance. In conclusion, this review provides a comprehensive insight into the future potential of MLCC for cutting tool performance enhancement.

1. Introduction

Nano coatings are a type of thin film technology that have been developed over the years to improve the properties of nearly every surface, from metals to plastics to fabrics. Nano coatings are created with extremely tiny particles that measure on the nanometer scale, and are capable of manipulating light, creating water repellence and stain resistance, and providing more advanced forms of protection. Since they are composed of particles smaller than a pixel, nano coatings offer a unique solution to many common problems, as they can be applied in thin layers to any surface (Mahdavian et al., 2022). The creation of nanotechnology dates back to the early 1980s, when researchers began to explore the properties of extremely small particles. At that time, the technology was limited to surface coatings, but as the industry matured, researchers began to investigate new ways to use nano technology. In the early 2000s, nano coatings began to gain traction in the scientific community and industry alike, as advances in nanotechnology became more widespread. The evolution of nano scale coatings has seen a significant push over the last decade. As nanotech has continued to evolve, so too has the range of nano-scale coatings available. These coatings have advanced to the point where they are now able to provide complete protection for surfaces, as well as enhanced mechanical, chemical and thermal properties (Sahoo et al., 2022). Additionally, these coatings can provide superior protection against abrasion, corrosion, and UV radiation. These advancements are especially beneficial in industries like automotive, marine, aerospace, and medical, which depend on having durable surfaces that can withstand friction and environmental conditions. The protective nano coatings also enable manufacturers to increase the lifespan and improve the performance of their products. The evolution of nano coatings has enabled progress in both industry and science. Not only are they used to enhance the durability of a surface, nano coatings can also be used to introduce desired optical, electrical, and chemical properties to the surface. They can also be used to increase the efficiency of specific processes, such as energy production from solar panels. Overall, the evolution of nano-scale coatings has been instrumental in solving some of the world's most pressing problems, from air and water pollution to energy security. Now, the technology is being used to enhance a variety of products and processes, and promises to bring about even more advances in the future (Xu et al., 2022).

The use of cutting tools has come to be an integral part of the industrial landscape and is integral to the manufacturing process. As such, it is important to understand the potential of different types of cutting tools and the potential applications of these tools. One of the most promising technologies in this regard, are Nano-scale multi-layered-composite coatings. Such coatings have been found to greatly enhance the performance of cutting tools and have been found to have numerous beneficial applications in various industries (Grigoriev et al., 2022). In this article, the potential of Nano-scale multi-layered-composite coatings for enhancing cutting tool performance is explored.

The use of cutting tools to shape and fabricate materials has long been a driving force of industrial innovation and efficiency. And while many advances have been made in recent decades to optimize the performance of cutting tools, there is still a lot of potential for further progress. One area of research that is proving to be particularly promising for this purpose is Nano-scale multi-layered composite coatings (NMCs). The NMC is a coating consisting of multiple layers of materials, each with a different composition. The layers are designed to work together in order to enhance the performance of the cutting tool. The most common types of material used in NMCs are Titanium Carbide, Vanadium carbide and Chromium Carbide, but other combinations are also possible. The benefit of using NMCs is two-fold: first, they act as a lubricant, reducing friction and wear during the cutting process; and second, they are able to improve the hardness of the cutting tool, making it more durable and resistant to damage. This means that the tool will last longer and require less frequent sharpening and replacement. NMC technology is still fairly new, but the potential applications are already wide-ranging and exciting (Galata et al., 2022). For instance, they can be used to increase the performance of drill bits, milling cutters, lathe tools, and turning tools. They are also being used to enhance the performance of cutting machines in a variety of industries such as aerospace, automotive, and electronics. Perhaps the most exciting potential application of NMCs is in the field of medical implants. Coated cutting tools can be used to create highly precise components for prosthetic limbs and implants, greatly improving the function and comfort of these prosthetics. At the same time, there are still some major challenges that must be addressed before NMCs can reach their full potential. For instance, the costs of producing NMCs are still relatively high, and the process of applying them to the cutting tools is labor-intensive. Additionally, like all coatings, NMCs are vulnerable to damage if they are not properly cared for, and their performance can be compromised if they become dirty or worn. Despite these challenges, the potential of nano-scale multi-layered composite coatings for cutting tools is still immense. As research and development in this field continues to progress, we can expect to see enhanced performance of cutting tools across a wide range of industries. And, with further advances in materials science and nanotechnology, the possibilities for even more sophisticated NMCs are practically limitless (Benti et al., 2022).

Nano technology plays a pivotal role in enhancing the performance of multi-layered composite coatings for cutting tools. By incorporating nanomaterials and utilizing nanoscale structures, these coatings can achieve significant improvements in cutting tool performance. One key advantage is the enhancement of hardness and wear resistance. The use of nanoparticles such as carbides, nitrides, and diamond-like carbon (DLC) allows for a more uniform dispersion within the coating matrix, creating a robust barrier against abrasive wear and reducing tool material loss during cutting operations. Moreover, nanostructured coatings can reduce friction and cutting forces, leading to smoother cutting and reduced tool wear. The integration of nanoscale lubricants further improves cutting efficiency (Cai et al., 2022). Nano technology also enables better control over the deposition process, resulting in improved adhesion between the coating and the substrate. This enhances coating integrity, extending the tool's lifespan by preventing delamination and chipping during cutting operations. Additionally, nanocomposite coatings exhibit improved thermal stability, withstanding high cutting temperatures without significant degradation. The incorporation of nanostructures also enhances heat dissipation, reducing the risk of thermal damage to the tool and workpiece. Moreover, nanostructured coatings contribute to achieving superior surface finishes, minimizing surface defects by reducing tool wear and frictional forces. In a nutshell, nano technology offers tailored coating design and provides a significant boost to the performance of multi-layered composite coatings, ultimately enhancing cutting tool performance and prolonging tool life (Babu et al., 2022).

2. Overview of multi-layered-composite coatings

Multi-layered composite coatings (MLCC) are a type of protective coating that is composed of multiple layers of different materials. These coatings are used in a variety of industries, including aerospace, automotive, and marine applications. By combining the properties of various materials, MLCC can provide superior performance in a variety of conditions (Vereschaka et al., 2022). Each layer of the coating provides a unique combination of properties that together form a stronger, more effective coating. The materials used in MLCC can include metal, polymer, ceramic, and other materials. Each layer of the coating is designed to provide specific properties, such as corrosion resistance, wear resistance, electrical insulation, and thermal insulation. One of the primary advantages of MLCC is their ability to provide superior performance in a varied machining conditions (Moganapriya et al., 2021).In particular, the combination of Al/Cu/Sn/Ni layers makes for an ideal material for many applications due to its excellent mechanical properties and corrosion resistance. In order to evaluate the macro and microstructure of this composite material, several tests must be conducted. At the macro level, the mechanical properties of the Al/Cu/Sn/Ni composite can be evaluated through tensile and compression testing. These tests measure the material's strength, elongation, and modulus of elasticity, as well as its ductility and fatigue resistance. The mechanical properties are also affected by the post-heat treatment process, so they can be compared to samples that were not heat-treated to assess the influence of the post-heat treatment. At the microstructure level, the Al/Cu/Sn/Ni composite can be assessed by examining the micrographs of the material (Singh et al., 2023). The tests measure the material's susceptibility to different types of corrosion and can provide insight into its performance in real-world applications. The evaluation of the macro and microstructure of Al/Cu/Sn/Ni composite produced by accumulative-roll-bonding (ARB) and post-heat treatment is a complex process that requires a combination of different tests. Mechanical testing can measure the strength, elongation, and modulus of elasticity of the material, while micrographs and SEM can reveal the microstructural characteristics of the material (Volosova et al., 2021). The efficiency of cutting tools can be improved by applying different coating techniques and one such technique is Filtered Cathodic Vacuum Arc Deposition (FCVAD). FCVAD is a cost-effective and environmentally friendly technique that has gained much attention in recent years due to its potential to increase the efficiency of cutting tools. This review will discuss the various aspects of FCVAD coating technique, its advantages and disadvantages, and the potential applications for improving the efficiency of cutting tools. FCVAD is a coating technique that is based on a cathode arc discharge in vacuum. In this technique, the coating material is heated and ionized by a cathode arc discharge and then deposited on the substrate surface. This process gives the coating material an extremely smooth surface topography and a fine grain structure which leads to increased tool life and improved cutting efficiency. The coating material can be tailored according to the application and it can be made from a variety of materials such as metals, ceramics, and polymers. The advantages of FCVAD coating technique include its cost-effectiveness, environmental friendliness, and ability to tailor the coating material according to the application (Oganyan et al., 2021).

The utilization of different coating combinations involving Nano materials has shown significant potential in enhancing the efficiency and performance of cutting tools under heavy cutting conditions. Nano materials such as titanium nitride (TiN), titanium aluminium nitride (TiAlN), and diamond-like carbon (DLC) coatings have been extensively studied and employed in the manufacturing of cutting tools. These coatings offer various advantages, including improved hardness, wear resistance, and thermal stability (Grigoriev et al., 2022).By combining different Nano materials in coatings, engineers can tailor the properties to suit specific cutting conditions. For example, a multilayered coating comprising TiN and TiAlN can provide a balance between hardness and toughness, resulting in enhanced tool life and wear resistance. Furthermore, the addition of DLC coatings can further improve the surface smoothness and reduce friction during cutting, leading to reduced tool wear and improved cutting efficiency (Beake et al., 2021).

The effectiveness of coating combinations is typically evaluated through cutting tests, measuring parameters such as tool wear, cutting forces, and surface finish. The aim is to achieve the optimal balance between hardness, toughness, adhesion, and thermal stability to withstand heavy cutting conditions (Meghwal et al., 2022).While the development of coating combinations for cutting tools is a complex and ongoing research area, the advancements in Nano materials have shown great promise in improving the efficiency and performance of cutting tools under heavy cutting conditions. Continued research and development in this field will likely lead to further advancements and the creation of even more effective cutting tools for demanding industrial applications (Galata et al., 2022).

3. Properties and benefits of multi-layered-composite coatings

Multi-layered-composite coatings are a unique type of coating that provides a wide range of benefits to many different types of surfaces. These coatings are made up of multiple layers, each layer offering a unique set of properties. The combination of these properties makes multi-layered-composite coatings a great choice for many applications. One of the primary benefits of multi-layered-composite coatings is their ability to provide superior protection to surfaces. In a nutshell, multi-layered-composite coatings offer excellent resistance to abrasion. This helps to ensure that the coating is able to withstand in different machining conditions, due to its excellent resistance to abrasion (Vereschaka et al., 2022).

Low field magnetic resonance (LFMR) is a relatively new technology that has recently been used for defect detection in multi-layered cylindrical composite structures. LFMR is a non-destructive evaluation (NDE) technique that can be used to identify and characterize defects in composite materials without damaging the structure. The application of LFMR for defect detection in multi-layered cylindrical composite structures has several advantages over other more traditional NDE methods, such as X-ray radiography and ultrasonic imaging. LFMR is capable of detecting defects in composite materials that may not be visible to X-ray radiography or ultrasonic imaging. This includes defects that are too small or too deep for traditional methods of NDE to detect. LFMR has the ability to detect any type of defect, from internal voids and cracks to delamination and matrix cracking (Babu et al., 2022). In addition,LFMR is a viable option for defect detection in multi-layered cylindrical composite structures due to its ability to analyze the internal structure and composition of materials. LFMR utilizes low-frequency magnetic fields and magnetic resonance techniques to identify variations in material composition, enabling the detection of defects or inconsistencies within the structure. It is a non-destructive testing method that can penetrate beneath the surface, making it capable of detecting subsurface defects such as delaminations or voids. LFMR provides quantitative data on parameters like thickness and defect dimensions, allowing for accurate defect characterization. With relatively fast inspection times, LFMR offers efficient defect detection in multi-layered cylindrical composite structures. LFMR has the capability to detect both linear and non-linear defects, making it ideal for use in multi-layered cylindrical composite structures (Naito et al., 2021).

The use of LFMR in defect detection for multi-layered cylindrical composite structures offers several advantages over traditional methods of NDE. LFMR is non-invasive, preserving the integrity of the structure and allowing for further evaluation of any detected defects. Furthermore, LFMR is a fast and cost-effective method, producing results much quicker than X-ray radiography or ultrasound scans, and at a significantly lower cost compared to traditional NDE techniques. Given these benefits, LFMR should be considered a viable option for defect detection in multi-layered cylindrical composite structures (Akhavan Attar et al., 2021).

In the aerospace and defense industry, Inconel DA 718 is a highly regarded alloy known for its exceptional corrosion and heat resistance, as well as its high strength and toughness. Machining Inconel DA 718 components requires special treatment to ensure their surfaces can withstand the harsh conditions they will encounter. One such treatment involves applying a bi-nano-multilayer coating composed of TiAlCrSiN (Titanium Aluminum Chromium Silicon Nitride) /TiAlCrN (Titanium Aluminum Chromium Nitride). While this coating already provides excellent resistance and durability, its performance can be further enhanced for machining Inconel DA 718 (Grigoriev et al., 2021). Optimization of the multiscale self-organization processes within the bi-nano-multilayer coating is a method to achieve this enhancement. Self-organization refers to the interaction of coating components, resulting in surface patterns and structures (Meghwal et al., 2022). By adjusting the parameters of the chemical, physical, and thermal processes used to form the coating, these self-organization processes can be optimized, leading to a more uniform and stable film over the Inconel DA 718 component. This optimization strengthens the bonding interfaces between the coating and the substrate, offering improved chemical, structural, and corrosion protection during machining. Additionally, it reduces abrasion, erosion, and galling, resulting in a more efficient machining process (Tao et al., 2021). The optimized coating also enhances the wear and friction resistance of Inconel DA 718 components, prolonging the lifespan of cutting tools and reducing the need for frequent maintenance and replacement. Consequently, optimizing the multiscale self-organization processes of the TiAlCrSiN/TiAlCrN bi-nano-multilayer coating proves to be an effective means of improving the performance of machined Inconel DA 718 components. The optimized coating provides enhanced chemical, structural, and corrosion protection, improved wear and friction resistance, and reduces abrasion, erosion, and galling, resulting in a more efficient and effective machining process. Nano Layer coating techniques are commonly employed in the manufacturing process of cutting tools, as depicted in Fig. 1, showcasing typical TiN and TiALN coated silicon carbide turning tool inserts (Kumar et al., 2021).

LFMR utilizes low magnetic fields to probe the atomic nuclei within the coating layers, allowing for accurate and non-destructive thickness measurement. This technology has found significant applications in the manufacturing industry, particularly in the field of cutting tools. By precisely determining the thickness of each layer in a multilayer coating, LFMR enables manufacturers to optimize the performance and durability of cutting tools. It aids in quality control processes, ensuring that the coating thickness meets the desired specifications, resulting in improved tool performance and extended tool life (Ramesh et al., 2022). Additionally, LFMR provides real-time measurements, allowing for efficient monitoring and adjustment of the coating process, leading to enhanced productivity and cost-effectiveness in manufacturing operations. In a nutshell, LFMR has proven to be a highly useful and practical technique for multilayer coating thickness measurement in cutting tools, enabling manufacturers to achieve higher precision and performance in their products (Liu et al., 2021).

Coating thickness is measured using Low field magnetic resonance (LFMR) through a process known as nuclear magnetic resonance (NMR). LFMR systems typically consist of a magnet, a radiofrequency (RF) coil, and a measurement instrument. The basic principle involves subjecting the sample, such as a cutting tool with a multilayer coating, to a low-intensity magnetic field generated by the magnet.The LFMR system emits RF pulses that excite the atomic nuclei within the coating layers. Each layer has a distinct NMR response based on its chemical composition and thickness. The RF coil detects the NMR signals emitted by the excited nuclei (Al-Amin et al., 2021). These signals are then processed and analyzed by the measurement instrument. By analyzing the NMR signals, the LFMR system can determine the coating thickness of each layer in the multilayer structure. The NMR response is influenced by factors such as the number of atomic nuclei, the types of nuclei present, and their relaxation properties. Through calibration and reference measurements, the LFMR system can establish correlations between the NMR signals and the coating thickness, allowing for accurate thickness measurements (Hashemi et al., 2021).

Coating thickness can be measured also using Low field Nuclear Magnetic Resonance (NMR) through a technique called NMR relaxometry. In this method, a low-intensity magnetic field is applied to the sample, such as a coated substrate or a coating film. The magnetic field causes the atomic nuclei within the coating material to align with the field.Once the nuclei are aligned, a radiofrequency (RF) pulse is applied to excite the nuclei and disrupt their alignment. As the nuclei return to their aligned state, they emit NMR signals that are detected by a coil or antenna surrounding the sample.The detected NMR signals are then processed to extract informa-

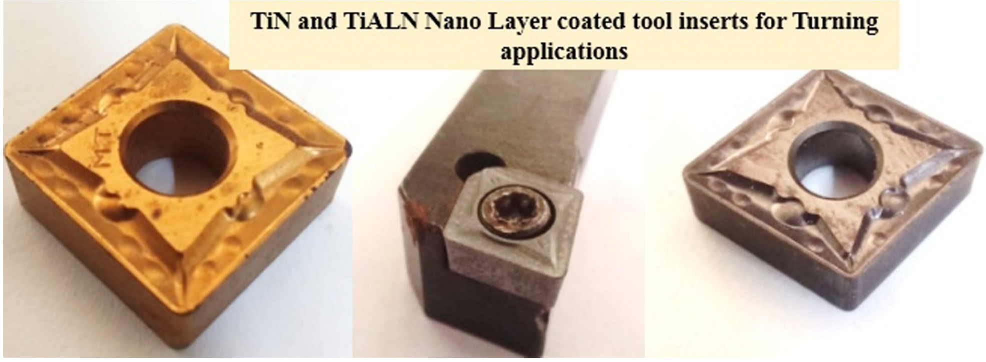

Fig. 1 Applications of Nano Layer coatings in cutting tool manufacturing.

tion about the coating thickness. The decay of the NMR signals, known as the relaxation behavior, is influenced by various factors, including the thickness of the coating layer. Thicker coatings tend to exhibit slower relaxation times compared to thinner coatings (Yu et al., 2021).

By analyzing the relaxation behavior of the NMR signals, mathematical models or calibration curves can be used to determine the coating thickness. These models establish correlations between the relaxation times and known coating thicknesses, allowing for accurate measurements.

Nano-scale coating wear measurement has become a critical technology in the ever-growing field of materials science (AlianMoghadam et al., 2021). As the materials used in engineering, industries and consumer products continue to evolve, the need for highly accurate measurement of wear on their surfaces has never been more important. The current standard for measuring wear is physical scratch tests, but these tests can be limited in accuracy and capability. To provide a more effective, accurate, and cost-effective tool, many researchers are now looking to Raman-sensing underlayers as a means of nano-scale coating wear measurement. Raman-sensing is a surface characterization technique that uses light to measure molecular vibrations for the purpose of monitoring molecular changes. The technique is based on the Raman effect, which is the inelastic scattering of light from molecules, resulting in a shift in the wavelength or frequency of the photons (Ali et al., 2022). By changing the incident light, or the direction of the light, Raman measurements can be taken from surfaces with nanoscale resolution. In the context of wear measurement, Raman-sensing underlayers can be applied to a range of surfaces in order to measure wear on a nanoscale. By measuring the changes in molecular vibration, scientists are able to gain an unprecedented level of accuracy in wear measurement. For instance, Raman-sensing has the capability to detect wear of a few nanometers, compared to 20–50 nm of scratch and wear tests. This higher resolution can be used to effectively identify and isolate the cause of wear and tear, informing decisions about the suitability of materials and the best solutions for their preservation. In recent years, Raman-based wear measurements have grown in popularity, due to their accuracy, affordability, and convenience. Further developments in the technology are likely to allow for more accurate measurements, as well as wider applications in a range of industries, such as biomedical, automotive, energy, and more. Ultimately, the Raman-sensing technique has the potential to revolutionize how we measure wear, by providing an effective and cost-efficient tool for nano-scale coating wear measurement (Abdolmajidi et al., 2022).

Wear and friction behavior of CrTiN (Chromium Titanium Nitride)/TiCN (Titanium Carbon Nitride) and CrTiN (Chromium Titanium Nitride)/CrCN (Chromium Carbon Nitride) multi-layer composite coatings has been a topic of discussion in tribology for several decades. These types of coatings are most often coated on tooling components which come into contact with other materials in machining, drilling and other manufacturing processes. The wear and friction behaviour of these coatings is of prime importance for their long-term performance and durability. The wear behaviour of materials is oftentimes determined by their tribology characteristics such as coefficient of friction, wear-resistance, abrasion behaviour and impact resistance (Lee et al., 2022). These tribology characteristics are in turn determined by the material's chemical composition and structure. In the case of CrTiN/TiCN and CrTiN/CrCN multi-layer composite coatings, the chemical composition of the substrate and the nanometers of the two coating layers provides an interesting and complex tribologicalbehaviour. CrTiN/TiCN coating layer typically consists of a thin chromium nitride layer which acts as the base and a thicker titanium nitride layer which serves as an isolation layer. It is the interaction of the two layers and their respective components which provide the wear and friction characteristics desired in this type of coating. The chromium nitride layer offers superior corrosion resistance and a smooth, low-friction surface while the titanium nitride layer allows for a certain degree of toughness and hardness. Similarly, CrTiN/CrCN multi-layer composite coatings typically have a thin chromium nitride layer as the substrate with a thicker chromium nitride layer as the outer layer (Calaph et al., 2022). In this type of coating, the chromium nitride layers help reduce friction, improve abrasion and scratching resistance and also reduce the galling effect due to frequent contact between the coated components. In general, CrTiN/TiCN and CrTiN/CrCN multi-layer composite coatings offer good wear and friction behavior. These coatings are mainly used for wearing parts and high-end components which come into frequent contact with other materials during their lifetime. Both of these types of coatings are ideal for machining, drilling, and other manufacturing processes due to their good tribological characteristics. They provide a good balance of wear and friction behavior, meaning that the coated components will be able to withstand frequent and intense contact without undergoing excessive wear. In summary, CrTiN/TiCN and CrTiN/CrCN multi-layer composite coatings offer excellent wear and friction behavior which makes them an ideal choice for components which require durable and long-term performance (Satya Prasad et al., 2021).

4. Cutting tool performance enhancement

In the tool industry, Nano-scale Multi Layered-Composite Coatings are used to increase the performance. This coating allows the coatings to adhesively attach to one another and better resist wear and tear. Additionally, Nano-scale Multi Layered-Composite Coatings are effective at enhancing the cutting action of a cutting tool (Singh et al., 2022). Due to the nature of Nano-scale Multi Layered-Composite Coatings, they are incredibly durable. Despite being made up of small pieces, Nano-scale Multi Layered-Composite Coatings have been found to be even more durable than traditional coating methods. Additionally, Nano-scale Multi Layered-Composite Coatings are less expensive to create than traditional coating methods. Due to the fact that Nano-scale Multi Layered-Composite Coatings are so effective, they are ideal for use in the tool industry (Rathnaraj et al., 2022).It reduces the force required to cut materials, improve tool life and performance, and enhance surface finish. Nano-scale coatings can be applied to cutting tools in a number of ways, including as a coating on the cutting edge, in the recesses of the tool, or as a layer between the tool and the work piece (Paturi et al., 2021). Nano-scale coatings can be a cost-effective way to improve the performance of cutting tools. They can provide benefits that are difficult to attain with other methods, such as precision and durability. Nano-scale coatings can be applied in a number of ways, making them versatile and useful in a variety of applications. Nano-scale coatings are cost-effective and provide a range of benefits that are difficult to achieve with other methods (Singh et al., 2023). Nanoscale coating has become an important tool for improving the performance of cutting tools. By coating cutting tools at the nanoscale, the hardness and toughness of the cutting tool is improved, leading to increased efficiency and durability. In addition, cutting tools coated with nanoscale materials such as titanium nitride and diamond-like carbon (DLC) are capable of reaching cutting speeds many times faster than tools without coatings. In order to achieve optimal results, cutting tools must be coated in such a way that they remain more resistant to wear (Dabees et al., 2022). In a nutshell, nanoscale coatings are also advantageous for corrosion resistance and lubricity of cutting tools. This can improve machining productivity, and prevent wear particles from adhering to the cutting tool. The Nanoscale coatings can offer tremendous benefits to cutting tool performance, including improved hardness, lubricity, and corrosion resistance, as well as better heat dissipation and improved control over machining forces. By taking advantage of the latest developments in nanoscale coating technology, manufacturers can drastically improve the efficiency and longevity of their cutting tools (Nankar, 2009).

5. Benefits of nano-scale multi layered-composite coatings

Nano-scale MLCC are effective at reducing the heat output of a surface while maintaining its function. This type of coating is most commonly used on aircraft surfaces, such as the wings and tail surfaces, to reduce the heat emissions that can cause turbulence and drag. Multi layered composite coatings are made up of several different materials, each with its own specific purpose. The different layers work together to create a coating that is highly effective at reducing the amount of heat that is emitted from the surface it is applied to. The outermost layer is made up of a material that is highly resistant to the elements, such as air and water (Ali et al., 2022). This layer is then covered in a second layer made up of a material that is highly heat-sensitive. When the heat from the object being coated is applied, the second layer will heat up more than the first, and will start to vaporize. The vaporized material then forms a thin film on the surface, and will protect the underlying layer from further damage. This process is repeated until the coating has been fully applied. Multi layered composite coatings are effective at reducing the heat output of a surface while maintaining its function.This type of coating is most commonly used on aircraft surfaces, such as the wings and tail surfaces, to reduce the heat emissions that can cause turbulence and drag. By using a multi-layered coating, it is possible to reduce the amount of heat that is emitted from the surface by up to 90%. This reduction in heat output can eliminate the need for air conditioning on aircraft, and can overall save the airline a significant amount of money. Another benefit of using a nano-scale multi-layered composite coating is that it can enhance the surface's durability (Song et al., 2022).

They can have a wide range of thermal behaviours, heat dissipation capabilities, and protective barriers. The benefits of Nano scale coatings are as follows.

(a) **Improved Durability:** Nano-scale MLCC provide improved protection against corrosion and abrasion, helping to extend the service life of components.
(b) **Enhanced Physical Properties:** Nano-scale MLCC are often used to improve the physical performance of parts; including improving the strength, hardness and wear resistance of components.
(c) **Improved Chemical Resistance:** Nano-scale MLCC can improve the resistance of components against a variety of different chemicals, including acidic, alkaline, and organic compounds.
(d) **Improved Thermal Properties:** Nano-scale MLCC help to improve the thermal properties of components, including increased heat resistance and better thermal insulation.
(e) **Improved Tribological Performance:** Nano-scale MLCC can improve the tribological (friction, lubrication and wear) performance of components, reducing the wear and tear on components during use.
(f) **Improved Optical Properties:** Nano-scale MLCC can be used to improve the optical properties of components, providing better clarity and light transmission.

Nano-scale multi-layered composite coatings for cutting tool performance have been a subject of extensive research. Several studies have highlighted the significant improvements in cutting tool performance achieved through the application of such coatings. Here are a few notable research results in this field:

(a) **Enhanced Hardness and Wear Resistance:** Research has shown that nano-scale multi-layered composite coatings can significantly increase the hardness and wear resistance of cutting tools. The layering of different materials at the nanoscale creates a barrier against wear, reducing tool degradation and extending tool life.

(b) **Reduced Friction and Improved Lubrication:** Coatings with nanoscale layers can offer reduced friction and improved lubrication properties. Research has demonstrated that these coatings can decrease the coefficient of friction between the tool and workpiece, leading to lower cutting forces, reduced heat generation, and improved machining performance.

(c) **Improved Adhesion and Coating Integrity:** The use of nano-scale multi-layered composite coatings has been found to enhance coating adhesion and integrity. The layering structure can improve the interfacial bonding between the coating and substrate, reducing the likelihood of delamination or spalling during machining operations.

(d) **Superior Thermal Stability:** Nano-scale multi-layered composite coatings exhibit excellent thermal stability, making them suitable for high-temperature machining applications. Research has shown that these coatings can maintain their mechanical and tribological properties even under extreme cutting conditions, such as high cutting speeds and temperatures.

(e) **Tailored Coating Properties:** The composition and thickness of individual layers in multi-layered coatings can be precisely engineered to achieve desired properties. Researchers have explored different combinations of materials, layer thicknesses, and deposition techniques to optimize coating performance, tailoring the coatings for specific cutting applications.

6. Deposition Techniques

Various depositing techniques are employed to create multilayer Nano coatings with precise control over thickness, composition, and structure. These techniques include physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), electroplating, and sol–gel deposition (Song et al., 2021).

6.1. Physical vapour deposition

PVD methods, such as magnetron sputtering and electron beam evaporation, involve the physical vaporization of coating materials followed by their condensation onto the substrate. PVD allows for excellent control of layer thickness and composition, making it suitable for creating complex multilayer structures.

6.2. Chemical vapour deposition

CVD involves the reaction of volatile precursor gases to deposit thin films on the substrate. It offers versatility in depositing a wide range of materials and allows for conformal coatings on complex geometries. Plasma-enhanced CVD (PECVD) utilizes plasma activation to enhance film growth and modify properties.

6.3. Atomic layer deposition

ALD is a highly controlled deposition technique that utilizes self-limiting surface reactions to deposit one atomic layer at a time. It offers exceptional control over film thickness and uniformity, making it ideal for creating ultrathin multilayer coatings with precise control over composition.

6.4. Electroplating

Electroplating involves the deposition of metal ions onto the substrate using an electric current. It enables the formation of thick coatings with high purity and uniformity. Electroplating is commonly used for creating metal-based multilayer coatings.

6.5. Sol-gel

Sol-gel deposition involves the synthesis of a colloidal solution (sol) that undergoes controlled hydrolysis and condensation reactions to form a gel. The gel is then deposited on the substrate and undergoes further heat treatment to form the desired coating. Sol-gel deposition is versatile and allows for the incorporation of nanoparticles and the formation of hybrid organic–inorganic coatings.

Each of these deposition techniques offers unique advantages and limitations in terms of film quality, control, and scalability. The choice of technique depends on the specific requirements of the multilayer Nano coating, such as composition, thickness, and desired properties, as well as the substrate material and geometry (Li et al., 2022; Raghavendra et al., 2021; Goyal et al., 2022).

7. Challenges faced in developing nano-scale multi-layered-composite coatings

Nanotechnology is one of the most rapidly advancing fields of science, with applications ranging from medicine to industry. Despite the potential of these coatings, there are several challenges that must be overcome in order to realize their full potential. The first challenge is the difficulty in manufacturing these coatings. The nano-scale size of the layers and the complexity of the multi-layered structure requires a high degree of precision and accuracy in the production process (Ganeshkumar et al., 2020). This precision requires specialized equipment and techniques, which can be costly and time consuming. Furthermore, the layers must be carefully monitored and controlled to ensure that they are properly formed. Another challenge is the complexity of the composition of the layers. Each layer is composed of a variety of materials, which must be precisely mixed and applied in order to achieve the desired properties. The composition of the layers must also be carefully monitored and adjusted as the coating is formed, as even small changes in the composition can drastically alter the properties of the coating. Finally, the durability of the coating must be verified. The nano-scale size of the layers and the complexity of the multi-layered structure makes the coating susceptible to wear and tear, as well as environmental factors (Singh et al., 2023). It is important to test the coating to ensure that it is able to withstand the intended use and environment. However, these coatings present a number of challenges, from the difficulty in manufacturing them to the complexity of the composition and the durability of the coating. With the right equipment, techniques, and testing, these challenges can be overcome and the full potential of these coatings can be realized (Kumar and Thirunavukkarasu, 2016).

One of the major challenges in developing nano-scale composite coatings is controlling the film morphology and the substrate surface. This is because the film morphology and the substrate surface can affect the performance of the coating. One way to control film morphology is to use a focused ion beam (FIB) to create nanoscale features on the film. FIB is an advanced tool that is used to create features on film that are smaller than 100 nm. The use of FIB can help to control film morphology by controlling the size and shape of the features. Another way to control film morphology is to use step coverage (Ganeshkumar and Venkatesh, 2022). Step coverage is a technique that is used to create a uniform film on the substrate. Step coverage is achieved by covering the substrate with a series of thin films. This method can be used to control film morphology by controlling the amount of coverage. Another way to control film morphology is to use an amorphous substrate. Amorphous substrates are substrates that do not have a well-defined shape. Amorphous substrates can be used to control film morphology by controlling the degree of crystallinity (Ganeshkumar et al., 2022c). Another way to control film morphology is to use a blend of two or more films. Blends of films can be used to control film morphology by controlling the interfacial properties between the films. Another way to control film morphology is to use a process called vacuum-assisted coating (VAC). VAC is a process that is used to apply a coating without having to contact the substrate. VAC can be used to control film morphology by controlling the deposition rate and the substrate temperature. All of these methods can be used to control film morphology. However, each method has its own advantages and disadvantages. The use of FIB is the most controllable method of controlling film morphology. FIB can be used to control the size and shape of the features on the film. FIB can also be used to create nanoscale features on the film. The use of step coverage is the least controllable method of controlling film morphology. Step coverage is achieved by covering the substrate with a series of thin films. Step coverage is not as controllable as FIB because the amount of coverage can vary. The use of an amorphous substrate is the least controllable method of controlling film morphology. Amorphous substrates can be difficult to control because the degree of crystallinity can vary. The use of a blend of two or more films is the most controllable method of controlling film morphology. Blends of films can be used to control film morphology by controlling the interfacial properties between the films. The use of VAC is the least controllable method of controlling film morphology. VAC is a process that is used to apply a coating without having to contact the substrate. VAC is less controllable than step coverage and FIB because the deposition rate and the substrate temperature can vary. Overall, the use of FIB, step coverage, amorphous substrates, and blends of films are the most controllable methods of controlling film morphology. VAC is the least controllable method of controlling film morphology (Ganeshkumar et al., 2022b).

The preparation of suitable nanocomposites for real applications in metal cutting operations is faced with numerous challenges. One significant challenge lies in achieving a uniform dispersion of nanoparticles within the matrix material. The agglomeration or poor dispersion of nanoparticles can lead to inconsistent performance and reduced mechanical properties. Additionally, controlling the size and shape distribution of nanoparticles proves to be a demanding task, as these factors greatly influence the properties of nanocomposites (Song et al., 2022). Establishing a strong and stable interface between the matrix material and nanoparticles is critical for efficient load transfer and improved mechanical properties, but achieving good interfacial bonding is challenging due to the large surface area and reactivity of nanoparticles. Another hurdle is the scalability of the synthesis process, as it needs to be efficient and reproducible while maintaining consistent quality (Ganeshkumar et al., 2022a). In terms of application challenges, compatibility with metal cutting conditions is a key consideration. Nanocomposites must be able to withstand high temperatures, stresses, and abrasive wear experienced during metal cutting. Ensuring their stability and performance under such harsh conditions can be quite challenging. Another crucial aspect is optimizing tool life and performance. While the goal is to improve these aspects, achieving significant enhancements while maintaining cost-effectiveness is a balancing act. The wear resistance and friction reduction properties of nanocomposites are critical in enhancing tool life and reducing cutting forces, but their complex interactions with the matrix material pose challenges in achieving the desired properties. Furthermore, nanocomposites should provide improved surface finish and effective chip evacuation during metal cutting operations. Striking the right balance between material properties to optimize surface finish and chip formation proves to be another challenge (Kumar et al., 2023).

8. Application of nano-scale multi-layered-composite coatings

Nano-scale multi-layered-composite coatings have emerged as a game-changer in the metal cutting tool manufacturing industry. These advanced coatings, composed of alternating layers of different materials at the nanoscale, offer superior performance and durability compared to traditional coatings. The application of such coatings on metal cutting tools significantly enhances their wear resistance, reduces friction, and improves cutting efficiency. The nanoscale architecture of these coatings provides excellent hardness and toughness, enabling the tools to withstand high-speed machining and prolonged use without significant deterioration. Furthermore, these coatings can also minimize chip adhesion and improve chip evacuation, leading to smoother and more precise cutting operations. With their remarkable attributes, nano-scale multi-layered-composite coatings have revolutionized the metal cutting tool manufacturing industry by enabling the production of tools that exhibit exceptional performance, longevity, and reliability (Kumar et al., 2023).In recent years, nano layer composites have become increasingly important in the field of defense due to their potential for producing more climate-resilient, stealthy, and lightweight materials. The most widely used nano layer composite in defense applications is carbon nanotube (CNT) technology. CNTs are extremely thin and lightweight, yet exceptionally strong, making them useful as both armor and shield material. CNTs have been used to create lighter, more resilient body armor for soldiers and personnel, as well as protective and heat-resistant armor plating for military vehicles of all kinds. In addition to CNTs, nanocomposites are also widely used in the creation of radar absorbent materials. These materials are designed to reduce or block the reflection of radar signals, making them highly effective at hiding or disguising military vehicles and personnel. Similarly, they can be used to create stealth aircraft that are less visible to infrared or radar detection (Sharma et al., 2023; Budarapu et al., 2014; Tejendra et al., 2019).

Apart from carbon nanotubes (CNTs), there are other carbon materials that can be used in multi-layered composite coatings for metal cutting applications. These carbon materials offer unique properties and can enhance the performance of cutting tools. Some of these materials include:

8.1 Graphene: Graphene is a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. It possesses exceptional mechanical strength, high thermal and electrical conductivity, and low friction. Graphene can be incorporated into composite coatings to improve wear resistance, reduce friction, and enhance cutting tool performance.

8.2 Carbon nanofibers (CNFs): CNFs are cylindrical nanostructures composed of carbon atoms. They exhibit high tensile strength, good thermal stability, and electrical conductivity. CNFs can enhance the mechanical properties and wear resistance of composite coatings when used as reinforcement materials.

8.3 Carbon nanodots: Carbon nanodots are small carbon nanoparticles with diameters typically less than 10 nm. They possess unique optical properties and can be used as additives in composite coatings to improve lubrication and reduce friction.

8.4 Carbon black: Carbon black is a fine powder consisting of small carbon particles. It has excellent electrical conductivity and thermal stability. Carbon black can be incorporated into coatings to enhance wear resistance and provide improved thermal dissipation.

8.5 Graphite: Graphite is a layered carbon material composed of stacked graphene layers. It exhibits good lubricity and thermal stability. By incorporating graphite into composite coatings, friction and wear can be reduced, resulting in improved cutting tool performance.

These carbon materials offer a range of properties suitable for enhancing the performance of multi-layered composite coatings in metal cutting applications. The choice of carbon material depends on the specific requirements of the coating, such as desired properties, cost-effectiveness, and process compatibility (Liu et al., 2022; Vereshchaka et al., 2014).

9. Summary

Nano technology is rapidly gaining recognition as a valuable tool for improving cutting tool performance. This review focuses on the potential of Nano-scale multi-layered-composite coatings, which provide a unique combination of properties including increased hardness, toughness, wear resistance, and adhesion. The review discusses the various processes used to create these coatings, as well as their advantages and disadvantages in comparison to other coating options (Ganeshkumar et al., 2022a, 2022b; Kumar et al., 2023). It is concluded that Nano-scale multi-layered-composite coatings offer significant benefits in increasing cutting tool performance, and further research into the optimization of their composition and deposition methods is recommended. This review article explores the potential of Nano-scale multi-layered-composite coatings as a means to enhance cutting tool performance. It examines the various nanomaterials used to create such coatings and their properties, as well as the effects these coatings have on cutting parameters such as wear and tool life. It further analyses the recent literature on Nano-scale multi-layered-composite coatings, and discusses their potential for wider use in a variety of industrial applications (Balguri et al., 2021; Vijayakumar et al., 2020; Kumar and Allamraju, 2019).

10. Conclusion

This review has shown that nanostructured-composite coatings have the potential to revolutionize the performance of cutting tools. The combination of Nano-sized components and different chemical compositions offers a variety of features and benefits which cannot be achieved by conventional coatings. Ina nutshell, Nano-scale multi-layered-composite coatings are a promising new avenue of research to improve the performance of cutting tools. Characterization techniques and simulation technologies have improved the understanding of how Nano-scale coatings behave. With further research, Nano-scale materials could potentially lead to superior cutting performance, increased tool life, and cost-effective manufacturing processes (Ganeshkumar et al., 2022c).

11. Scope for future research

Nano-scale multi-layered-composite coatings are a relatively novel area of research with a wide range of potential applications in the cutting tool industry. These coatings represent a promising approach to enhancing cutting tool performance, potentially offering increased cutting speeds, improved wear resistance and better chip formation. In order to further develop this technology and its applications, there is great potential for further research. The most immediate scope for research is to explore the properties and applications of these coatings in more detail. Investigations into the interaction between different layers and the influence of different coating materials on the performance of the cutting tool would provide valuable insights into the practical use of these coatings. Long-term trials should also be conducted to assess the durability of the cutting tool and the potential for sustained performance enhancements. Research into the potential of nanocomposite coatings in other tool-based applications would also be beneficial. By exploring the potential of these coatings in different settings, such as in end-milling and drilling, researchers can gain a better understanding of the potential of these coatings across the tooling industry, and identify the optimal conditions in which they can be used to improve performance. In addition to practical research, there is also the potential for theoretical investigations into the mechanisms of these coatings. Further research into the chemical, mechanical and tribological properties of these coatings and their interactions with the cutting tool would enable researchers to gain a better understanding of their performance and develop more effective coatings to meet the needs of the cutting tool industry. Research into different methods of coating deposition may also be beneficial.

By exploring different approaches to the application of the coating, such as laser processing, sputter deposition and electroplating, researchers can ascertain the most efficient and cost-effective methods of coating application. This may also extend to optimising the deposition of multiple layers, in order to ensure the most effective coating is applied. Finally, a fundamental area of research is the efficacy of the coating in different materials, which is of particular importance given the wide variety of materials used in the cutting tool industry. Different materials may interact differently with the coating, thus impacting the performance of the cutting tool. With further research, these coatings have the potential to revolutionise the cutting tool industry (Ganeshkumar et al., 2022a, 2022b; Kumar et al., 2023). Some research are added here to represents the applications and utilizations of different materials i.e., ultra high quantum efficiency constructed by lanthanide (Li et al., 2022); nanomaterials alloys (Yang et al., 2023; Gan et al., 2023; Xie et al., 2021), high thermal expansion and oxygen insulation (Lai et al., 2023) and high efficiency materials (Tong et al., 2016; Sun et al., 2023; Gao et al., 2023).

Funding

Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2023R399), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Authors' contribution

All authors are equally contributed in the research work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdolmajidi, M., Cheraghi, A., Joshaghani, A.H., Mazaheri, H., 2022. Design, processing and evaluation of CuO, MgO and TiO2 nano-coatings absorbing electromagnetic waves based on epoxy paint. Nano-Struct. Nano-Obj. 32, 100911.

Akhavan Attar, A., Alavi Nia, A., Mazaheri, Y., Ghassemali, E., 2021. Improving the fracture toughness of multi-layered commercial pure aluminum via warm accumulative roll bonding. Int. J. Adv. Manuf. Technol. 116 (11), 3603–3617.

Al-Amin, M., Abdul-Rani, A.M., Danish, M., Rubaiee, S., Mahfouz, A.B., Thompson, H.M., Ali, S., Unune, D.R., Sulaiman, M.H., 2021. Investigation of coatings, corrosion and wear characteristics of machined biomaterials through hydroxyapatite mixed-EDM process: A Review. Materials 14 (13), 3597.

Ali, Z.Z., Mahdi, B.S., Althamer, A.D., 2022. Studying the effect of multicomponent nano-coating alloy on hydrogen embrittlement of AISI 1018 steel by gas-phase process. Al-Qadisiyah J. Eng. Sci. 15 (1).

Ali, Z., Singh, A.K., Thakare, O., Tiger, C., 2022. Studies of Nanomechanical and Wear Testing Methods of Thermal Sprayed Coatings. Tribol. Characteriz. Surf. Coat., 239–252

AlianMoghadam, H., Jabbari, M., Daneshmand, S., RasouliJazi, S., Khosravi, A., 2021. Investigation of the TiO2/SiC/SiO2 coating effect on the wear rate of needle graphite electrode by using electrical discharge machining. ADMT J. 14 (2), 65–71.

Babu, A., Aazem, I., Walden, R., Bairagi, S., Mulvihill, D.M., Pillai, S. C., 2022. Electrospun nanofiber based TENGs for wearable electronics and self-powered sensing. Chem. Eng. J. 139060

Balguri, Praveen Kumar, Harris Samuel, D.G., Thumu, Udayabhaskararao, 2021. A review on mechanical properties of epoxy nanocomposites. Mater. Today: Proc. 44 (Part 1), 346–355. https://doi.org/10.1016/j.matpr.2020.09.742. ISSN 2214-7853.

Beake, B.D., Bergdoll, L., Isern, L., Endrino, J.L., Fox-Rabinovich, G. S., Veldhuis, S.C., 2021. Influence of probe geometry in micro-scale impact testing of nano-multilayeredTiAlCrN/NbN coatings deposited on WC-Co. Int. J. Refract Metal Hard Mater. 95, 105441.

Benti, H.G., Woldeyohannes, A.D., Yigezu, B.S., 2022. Improving the efficiency of cutting tools through application of filtered cathodic vacuum arc deposition coating techniques: A review. Adv. Mater. Sci. Eng. 2022.

Budarapu, P.R., Yb, S.S., Javvaji, B., et al, 2014. Vibration analysis of multi-walled carbon nanotubes embedded in elastic medium. Front. Struct. Civ. Eng. 8, 151–159. https://doi.org/10.1007/s11709-014-0247-9.

Cai, F., Wang, J., Zhou, Q., Zhang, S., Zheng, J., Wang, Q., Kim, K. H., 2022. Reduced delamination and improved cutting performance of TiAlSiN multilayer coated cutter by tailoring the adhesion layers and intermediate layers. Wear 488, 204135.

Calaph, Y.C., Subramanian, K.M., Nakandhrakumar, R.S., Sowrirajan, M., 2022. Experimental tool life and wear analysis of different thickness pecvdTiAlSiNnanocoated cutting tool inserts. Proc. Instit. Mech. Engineers Part E: J. Process Mech. Eng. 09544089221080029

Dabees, S., Mirzaei, S., Kaspar, P., Holcman, V., Sobola, D., 2022. Characterization and evaluation of engineered coating techniques for different cutting tools. Materials 15 (16), 5633.

Galata, E., Veziri, C.M., Theodorakopoulos, G.V., Romanos, G.E., Pavlatou, E.A., 2022. Composite GO/ceramic membranes prepared via chemical attachment: characterisation and gas permeance properties. Membranes 12 (12), 1181.

Gan, M., Chong, X., Yu, W., Xiao, B., Feng, J., 2023. Understanding the ultralow lattice thermal conductivity of monoclinic RETaO4 from acoustic-optical phonon anti-crossing property and a comparison with ZrO2. J. Am. Ceram. Soc. 106 (5), 3103–3115. https://doi.org/10.1111/jace.18988.

Ganeshkumar, S., Paranthaman, P., Arulmurugan, R., Arunprakash, J., Manickam, M., Venkatesh, S., Rajendiran, G., 2022b. Performance of multi-layerednano coated cutting tools in high-speed machining: A review. Int. J. Photoenergy, 1–8.

Ganeshkumar, S., Deepika, T., Haldorai, A., 2022c. A supervised machine learning model for tool condition monitoring in smart manufacturing. Def. Sci. J. 72 (5), 712–720.

Ganeshkumar, S., Venkatesh, S., 2022. Manufacturing techniques and applications of multifunctional metal matrix composites. Funct. Compos. Mater.: Manuf. Technol. Exp. Appl., 157

Ganeshkumar, S., Sureshkumar, R., Sureshbabu, Y., Balasubramani, S., 2020. A review on cutting tool measurement in turning tools by cloud computing systems in industry 4.0 and IoT. GIS Sci. J. 7 (8), 1–7.

Ganeshkumar, S., Singh, B.K., Kumar, S.D., Gokulkumar, S., Sharma, S., Mausam, K., Li, C., Zhang, Y., Tag Eldin, E.M., 2022a. Study of wear, stress and vibration characteristics of silicon carbide tool inserts and nano multi-layered titanium nitride-coated cutting tool inserts in turning of SS304 steels. Materials 15 (22), 7994.

Gao, S., Wang, H., Huang, H., Kang, R., 2023. Molecular simulation of the plastic deformation and crack formation in single grit grinding of 4H-SiC single crystal. Int. J. Mech. Sci. 247,. https://doi.org/10.1016/j.ijmecsci.2023.108147 108147.

Goyal, A., Kapoor, H., Jayahari, L., Saxena, K.K., Salmaan, N.U., Mohammed, K.A., 2022. Experimental investigation to analyze the mechanical and microstructure properties of 310 SS performed by TIG welding. Adv. Mater. Sci. Eng., 2022

Grigoriev, S.N., Vereschaka, A.A., Volosova, M.A., Sitnikov, N.N., Sotova, E.S., Seleznev, A.E., Bublikov, J.I., Batako, A.D., 2021. Improved efficiency of ceramic cutting tools in machining hardened steel—an application with nanostructured multilayered coatings. In: Handbook of Modern Coating Technologies. Elsevier, pp. 381–433.

Grigoriev, S., Vereschaka, A., Zelenkov, V., Sitnikov, N., Bublikov, J., Milovich, F., Andreev, N., Sotova, C., 2022. Investigation of the influence of the features of the deposition process on the structural features of microparticles in PVD coatings. Vacuum 202, 111144.

Hashemi, S., Parvin, N., Valefi, Z., Parvizi, S., 2021. Experimental investigation and parameter optimization of Cr2O3 atmospheric plasma spray nanocoatings. Synthesis and Sintering 1 (3), 143–150.

Kumar, P.S.S., Allamraju, K.V., 2019. A review of natural fiber composites [Jute, Sisal, Kenaf]. Mater. Today: Proc. 18 (Part 7), 2556–2562. https://doi.org/10.1016/j.matpr.2019.07.113. ISSN 2214-7853.

Kumar, C.M.P., Chandrashekarappa, M.P.G., Kulkarni, R.M., Pimenov, D.Y., Giasin, K., 2021. The effect of Zn and Zn–WO3 composites nano-coatings deposition on hardness and corrosion resistance in steel substrate. Materials 14 (9), 2253.

Kumar, A., Kumar, D., Faisal, N., Sharma, A., Kumar Ansu, A., Goyal, A., Kumar, D., 2023. Application of 3D printing technology for medical implants: a state-of-the-art review. Adv. Mater. Process. Technol., 1–16

Kumar, R.R., Kumar, A., Kumar, A., Ansu, A.K., Goyal, A., Saxena, K.K., Prasad, J.L., 2023. Thermal simulation on friction stir welding of AA6061 aluminum alloy by computational fluid dynamics. Int. J. Interact. Design Manuf. (IJIDeM), 1–11.

Kumar, S.G., Thirunavukkarasu, V., 2016. Investigation of tool wear and optimization of process parameters in turning of EN8 and EN 36 steels. Asian J. Res. Social Sci. Human. 6 (11), 237–243.

Lai, L., Gan, M., Wang, J., Chen, L., Liang, X., Feng, J., Chong, X., 2023. New class of high-entropy rare-earth niobates with high thermal expansion and oxygen insulation. J. Am. Ceram. Soc. https://doi.org/10.1111/jace.19077.

Lee, H., Kim, J., Park, J., Kim, J., 2022. Analysis of tool wear and roughness of graphite surfaces machined using MCD and NCD-coated ball endmills. Micromachines 13 (5), 766.

Li, X., Deng, J., Lu, Y., Duan, R., Ge, D., 2022. Machinability investigation and sustainability assessment of dry cutting AISI1045 steel using tools configured with shark-skin-inspired structures and WS2/C coatings. Int. J. Precis. Eng. Manuf.-Green Technol. 9 (1), 83–106.

Li, G., Huang, S., Li, K., Zhu, N., Zhao, B., Zhong, Q., Wang, D., 2022. Near-infrared responsive Z-scheme heterojunction with strong stability and ultra-high quantum efficiency constructed by lanthanide-doped glass. Appl. Catal. B 311,. https://doi.org/10.1016/j.apcatb.2022.121363 121363.

Liu, F., Han, Y., Guo, X., Wang, C., Zhang, K., 2021. Adhesion and machining performance of PVD AlCrN coatings with an ion beam/laser textured substrate. Surf. Coat. Technol. 423, 127607.

Liu, Y., Yu, S., Shi, Q., Ge, X., Wang, W., 2022. Multilayer coatings for tribology: A mini review. Nanomaterials 12 (9), 1388.

Mahdavian, M.M., Khodabandeh, A.R., Jafarian, H.R., Mirdamadi, S., 2022. Evaluation of the macro/microstructure of Al/Cu/Sn/Ni multi-layered composite produced by accumulative-roll-bonding (ARB) and post-heat treatment. J. Alloys Compd. 925, 166711.

Meghwal, A., Singh, S., Anupam, A., King, H.J., Schulz, C., Hall, C., Munroe, P., Berndt, C.C., Ang, A.S.M., 2022. Nano-and micro-mechanical properties and corrosion performance of a HVOF sprayed AlCoCrFeNi high-entropy alloy coating. J. Alloys Compd. 912, 165000.

Moganapriya, C., Vigneshwaran, M., Abbas, G., Ragavendran, A., Ragavendra, V.H., Rajasekar, R., 2021. Technical performance of nano-layered CNC cutting tool inserts–An extensive review. Mater. Today:. Proc. 45, 663–669.

Naito, M., Kozawa, T., Kondo, A., CC, H., 2021. Smart powder processing for excellent advanced materials and its applications. KONA Powder Part. J. 2023001

Nankar, A.S., 2009. A review of experimental wear analysis of assorted single layer coating on base material HSS M-42. J. Mater. Sci. Manuf. Technol. 6 (1), 41–52.

Oganyan, M., Vereschaka, A., Volosova, M., Gurin, V., 2021. Influence of the application of wear-resistant coatings on force parameters of the cutting process and the tool life during end milling of titanium alloys. Mater. Today:. Proc. 38, 1428–1432.

Paturi, U.M.R., Cheruku, S., Geereddy, S.R., 2021. Process modeling and parameter optimization of surface coatings using artificial neural networks (ANNs): State-of-the-art review. Mater. Today:. Proc. 38, 2764–2774.

Raghavendra, C.R., Basavarajappa, S., Sogalad, I., 2021. Grey relational analysis for optimization of wear parameters and surface roughness on nano composite coating. J. Indian Chem. Soc. 98, (10) 100171.

Ramesh, V., Stratmann, N., Schaufler, V., Angelov, S.D., Nordhorn, I.D., Heissler, H.E., Martínez-Hincapié, R., Čolić, V., Rehbock, C., Schwabe, K., Karst, U., 2022. Mechanical stability of nanocoatings on clinically applicable electrodes, generated by electrophoretic deposition. Adv. Healthc. Mater. 2102637

Rathnaraj, J.D., Dinesh, C., Velmurugan, R., Adithya, A., 2022. Effect of particle size on TiO2-polystyrene nanoparticles contact angle for hydrophobicity behavior. Proc. Mater.: Today.

Sahoo, S.K., Kuchipudi, S., Narasimha Rao, R., Buragohain, M.K., Chaitanya, C.S., 2022. Application of low field magnetic resonance for defect detection in multi-layered cylindrical composite structures. Nondestruct. Test. Evaluat. 37 (1), 22–40.

Satya Prasad, S.V., Prasad, S.B., Singh, S., 2021. Nanostructured 2D Materials as Nano Coatings and Thin Films. In: Advanced Applications of 2D Nanostructures. Springer, Singapore, pp. 55–72.

Sharma, S., Goyal, A., Pandey, A., Garimella, A., 2023. Effect of graphene nano platelets during fabrication of Al based metal matrix composite. AIP Conference Proceedings vol. 2492, no. 1.

Singh, P., Ansu, A.K., Sharma, R.K., Kumari, P., Kumar, A., Kumar, R., 2023. Development, thermal properties, and reliability testing of eutectic polyethylene glycol as phase change materials for thermal energy storage applications. Int. J. Thermophys. 44 (3), 39.

Singh, B.K., Chauhan, N., Mishra, A.K., Yadhuvanshi, A.A., Kumar, A., Ansu, A.K., Goyal, A., 2023. Experimental investigation of welding parameters to enhance the impact strength using gas tungsten arc welding. Int. J. Interact. Des. Manuf. (IJIDeM), 1–8.

Singh, J., Gill, S.S., Dogra, M., Singh, R., Singh, M., Sharma, S., Singh, G., Li, C., Rajkumar, S., 2022. State of the art review on the sustainable dry machining of advanced materials for multifaceted engineering applications: Progressive advancements and directions for future prospects. Mater. Res. Express.

Singh, D., Saini, A., Goyal, A., Abass, M.A., Prakash, C., Saxena, K. K., 2023. Design and development of modified tin oxide nanostructures for structural and optical applications. Int. J. Interact. Des. Manuf. (IJIDeM), 1–10.

Song, W., Wang, S., Lu, Y., Zhang, X., Xia, Z., Sun, K., Xin, G., 2021. Effect of MoS2/PTFE coatings on performance of Si3N4/TiC ceramics in dry sliding against WC/Co. Ceram. Int. 47 (9), 12631–12640.

Song, J., Zhang, Y., He, Y., Zhang, S., Li, H., Xiang, Y., Fan, Y., Song, R., Liu, B., 2022. Synthesis of Ni–B/diamond-Y2O3 binary nano-composite coatings and research on corrosion resistance and wear resistance of coatings with different pulse frequencies. J. Solid State Electrochem., 1–15

Sun, X., Chen, Z., Sun, Z., Wu, S., Guo, K., Dong, Z., Peng, Y., 2023. High-Efficiency utilization of waste shield slurry: A geopolymeric Flocculation-Filtration-Solidification method. Constr. Build. Mater. 387,. https://doi.org/10.1016/j.conbuildmat.2023.131569 131569.

Tao, C., Jin, M., Yao, H., Wang, D.A., 2021. Dopamine based adhesive nano-coatings on extracellular matrix (ECM) based grafts for enhanced host–graft interfacing affinity. Nanoscale 13 (43), 18148–18159.

Tejendra, G.K., Pattabhi, B.R., Sivakumar, C.R., Sastry Sudhir, Y.B., Marco, P., Stephane, B.P., 2019. Advances in carbon based nanomaterials for bio-medical applications. Curr. Med. Chem. 26 (38). https://doi.org/10.2174/0929867326666181126113605.

Tong, X., Zhang, F., Ji, B., Sheng, M., Tang, Y., 2016. Carbon-coated porous aluminum foil anode for high-rate, long-term cycling stability, and high energy density dual-ion batteries. Adv. Mater. (Weinheim) 28 (45), 9979–9985. https://doi.org/10.1002/adma.201603735.

Vereschaka, A., Volosova, M., Sitnikov, N., Milovich, F., Andreev, N., Bublikov, J., Sotova, C., 2022. Influence of the Nanostructure Parameters of Wear-Resistant Coatings on the Properties of Carbide Tools. In: Global Congress on Manufacturing and Management. Springer, Cham, pp. 135–144.

Vereschaka, A., Milovich, F., Migranov, M., Andreev, N., Alexandrov, I., Muranov, A., Mikhailov, M., Tatarkanov, A., 2022. Investigation of the tribological and operational properties of (Mex, Moy, Al1-(x + y)) N (Me–Ti, Zr or Cr) coatings. Tribol. Int. 165, 107305.

Vereshchaka, A.A., Vereshchaka, A.S., Mgaloblishvili, O., Morgan, M.N., Batako, A.D., 2014. Nano-scale multilayered-composite coatings for the cutting tools. Int. J. Adv. Manuf. Technol. 72, 303–317.

Vijayakumar, Y., Nagaraju, P., Yaragani, V., Parne, S.R., Awwad, N. S., Ramana Reddy, M.V., 2020. Nanostructured Al and Fe co-doped ZnO thin films for enhanced ammonia detection. Phys. B: Condens. Matter 581,. https://doi.org/10.1016/j.physb.2019.411976. ISSN 0921-4526 411976.

Volosova, M., Vereschaka, A., Andreev, N., Sotova, C., Bublikov, J., 2021. Improvement of the performance properties of cutting tools using the multilayer composite wear-resistant coatings based on nitrides of Cr, Mo, Zr, Nb, and Al. Mater. Today:. Proc. 38, 1421–1427.

Xie, J., Chen, Y., Yin, L., Zhang, T., Wang, S., Wang, L., 2021. Microstructure and mechanical properties of ultrasonic spot welding TiNi/Ti6Al4V dissimilar materials using pure Al coating. J. Manuf. Process. 64, 473–480. https://doi.org/10.1016/j.jmapro.2021.02.009.

Xu, N., Wang, C., Yang, L., Barimah, E.K., Jose, G., Neville, A., Morina, A., 2022. Nano-scale coating wear measurement by introducing Raman-sensing underlayer. J. Mater. Sci. Technol. 96, 285–294.

Yang, J., Shang, L., Sun, J., Bai, S., Wang, S., Liu, J., Ma, D., 2023. Restraining the Cr-Zr interdiffusion of Cr-coated Zr alloys in high temperature environment: A Cr/CrN/Cr coating approach. Corros. Sci. 214,. https://doi.org/10.1016/j.corsci.2023.111015 111015.

Yu, Q., Zhou, T., He, Y., Liu, P., Wang, X., Jiang, Y., Yan, J., 2021. Annealed high-phosphorus electroless Ni–P coatings for producing molds for precision glass molding. Mater. Chem. Phys. 262, 124297.