Review Article

Improving the Efficiency of Cutting Tools through Application of Filtered Cathodic Vacuum Arc Deposition Coating Techniques: A Review

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The challenge of enhancing cutting tool life has been dealt with by many research studies. However, this challenge seems endless with growing technological advancement which brings about incremental improvement in tool life. The objective of this review paper is focused at assessing filtered cathodic vacuum arc deposition techniques applied on cutting tools and their effect on tool efficiency. The paper particularly picks filtered cathodic vacuum arc deposition (FCVAD) among other well-identified methods of coating like the Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD). Filtered Cathodic Vacuum Arc Deposition is the state of art in the coating technology finding wide application in the electronics industry and medical industry in addition to the machining industry, which is the concern of this review paper. This review is made in order to summarize and present the various techniques of FCVAD coatings and their applications, as investigated by various researches in the area.

1. Introduction

Researchers have been working for long on identifying and evaluating factors determining tool efficiency. As it is stated by [1], these research efforts paved the way for the generation of improved models of tool wear. These improved models simplify the resolving of challenges related to the modern-day machining technology, which focuses at continuous life extension of cutting tools while maintaining high-speed cutting to the maximum possible. Obviously, mitigating these challenges in turn makes productivity and improvement of quality possible along with its benefits of economizing energy and material consumption [2–13].

An ideal property of tool materials may be considered to fulfill, for instance, high hardness along with good toughness that includes chemical stability at high operating temperatures. However, normally hardness and toughness do not coexist (restricting dualism). Therefore, in due course of time, research findings have come up with various cutting tools under composite materials to solve such challenges [5–7].

Optimization of hard materials and metals has been key area of research since long time [11]. However, currently, thermomechanical stresses, the tool material structure and properties should provide maximum resistance to the destruction of tool contact regions [5–7]. If the loads around the cutting area of the tool do not surpass the limits of strength characteristics of the tool material, that will have an impact of change in the structure of the material in the specific area due to work hardening [8–10].
protective coatings became an option available to enhance the efficiency of tools. Protective coatings are able to deliver required properties of tool materials like high level of hardness combined with required toughness. Lots of research works have been done on materials engineering since long time up to the current findings of superhardness of multielement materials. Research studies on hard films have established the fact that coated materials exhibit improved mechanical properties compared to uncoated ones. Moreover, cutting materials with coating layers also have found wider applications in the industry. Researches made in this area discovered that it is possible to make structures of coating sublayers of tool material with better capability of standing the thermomechanical load conditions faced in the machining process compared to single layer coatings [7, 12]. On this basis, deposition of multilayer coatings on tools surfaces has been recognized as effective [14, 15].

Generally, one can very well notice the characteristics of thin films to be somewhat different from the ones shown by material in bulk form. Obviously, there is a wide difference in property between them. On the start, Faraday’s experiments have brought significant move forward in the history of thin film technology through the electrodeposition of metals. Through this technology, a major control of deposition parameters was achieved and thin film generation was improved by new and quality deposition techniques through time. Consequently, applications of thin coatings expanded to many new fields like applications in optics and electronic devices [16].

2. Filtered Cathodic Vacuum Arc Deposition (FCVAD)

The major output expected from tools coated with a state-of-the-art technology is a maximized effective time of the cutting operation before failure, under difficult machining conditions. In order to meet this coating design, the investigations on wear mechanisms and the mitigating coating design principles enable us to make a summary of the basic parameters for the coatings. Based on this, coatings on cutting tools are expected to have fracture resistance up to 4000 MPa and keep their material properties up to 1100 C. In the meantime, at high temperatures, the mechanical, thermal, and physical properties which include elastic modulus, hardness, coefficient of thermal expansion, etc., are required not to reach hazardous stresses. Generally, the coatings should sufficiently stand the cyclic thermomechanical loads and resist macro/microfractures, liquid/solid phase diffusion reaction, and corrosion and wear at increased temperatures at the tool-work interface [17–22].

However, the intermediary role of the coating design required and more other factors demand a state-of-the-art, standard type of coating which has multilayers and composite in nature [23]. This type of coating which is also called nano-multilayered composite coating (NMCC) is considered to be effective in improving the challenges of tool life in metals machining processes [24]. Therefore, in this coating, every layer is linked to a designed encoded function. This means that the multilayered composite coatings basic elements shall be well analyzed on the basis of their desired functions to meet the functional requirements of the whole coating [14, 17, 25–27].

Having discussed the design requirements of properties and compositions of the multilayer coatings, now, it will be necessary to state the different possible methods of deposition of coatings. The governing methods to get hard coatings for cutting tools which have found wide applications since the beginning of the history of hard coatings are Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) [28]. In the 1970s, it is reported that CVD along with dedicated carbide substrates did well as pioneer in commercializing coated inserts [29]. Following it, the PVD process began to be applied widely with arc ion plating in the 1990s. Ever since, both of the CVD process and the PVD processes have evolved greatly [30–33]. Nowadays, it has become necessary to choose appropriate tool materials on the basis of the planned machining processes [34, 35]. In the meantime, efforts are required to offer solutions for industrial needs and challenges, with eco-friendly machining, enhanced accuracy and efficiency, improved tool life, and capability of machining hard to cut materials through working out on the development of innovative coating techniques like the FCVAD methods. FCVAD method has been identified to have special rewards compared to the CVD and PVD coating methods [36–39]. The following section describes the benefits gained by the new FCVAD method of coating compared with other methods of coatings.

2.1. Summary of Merits of FCVAD over Other Coating Methods. With the advancement of coating technologies, an evolution of a new method called "filtered cathodic vacuum arc deposition (FCVAD)" came up with a number of benefits mitigating the existing different types of coating related challenges. With this method, it was managed to regulate deposition parameters separately. This additionally contributed to comprehending the film growth processes easily. The advancement in the technology has, for instance, enabled regulation of substrate temperature independently of the control of deposition rate. Also, the energy of the atoms can further be specified more precisely and no working gas is required to generate the arc unlike other PVD processes [40–42].

CVD process has been an extensively applied materials-processing technology enabling deposition of various materials and large applications such as wear resistant coatings, thin film semiconductor devices, and biocompatible coatings. It is mainly applied in the production or formation of solid thin film development. However, CVD coating has been found to have gaps in ways of resisting the chipping challenge on cutting tools. This problem was known to arise from the fact that these coatings are developed at a temperature, as high as approximately 1000°C. Obviously, it is known that, at this temperature, the constituents of tool substrates like tungsten, carbon, and cobalt migrate to join the coating materials. Consequently,
A brittle layer is created at the boundary of the substrate and the coating [29, 43, 44].

Moreover, [37, 45, 46] found that CVD process is subjected to cobalt fragile conditions at the interface of coating-substrate. This situation minimizes the adhesion strength of the coating and therefore increases the tendency of brittle microfracture of the tools [37, 47].

On the other hand, the primary challenge faced in arc evaporation method is the existence of macroparticles of the cathodic material which is found within the plasma stream. This makes arc evaporation methods not qualified to be applied in fields of electronics and optics where coating technologies find wide application [48–52]. Nevertheless, researches have resulted in considerable progress over the past three decades in reducing macrodroplets through applying various forms of filters [53].

The FCVAD technique has been applied to deposit extensive range of materials with excellent properties. One of the major advantages delivered by this method of coating is that it applies filter to minimize the macrodroplets formed on the coating which adversely affect the property and performance of the coatings [37, 54].

FCVAD deposition technique is not limited to the advantages listed above; another influential factor of NMCC, the structure, has a crucial role in relation to fatigue strength of multilayer coating developed by FCVAD setup. Therefore, the idea of “coating structure,” which permits a major enhancement in tool life, is explained by [17, 55, 56]. In this explanation, the deposition of coatings on tools is supposed to be established on a nanocrystalline grain structure with ultrafine materials and super multilayered architecture with nanolevel thicknesses of the layers, which enable enlarged area of granular as well as interlayer boundaries [57]. The characteristics of this structure assume high resistance to fracture under complex external influences, even under conditions of sporadic thermomechanical loads. Consequently, S.N. Grigoriev and A.A. Vereshchaka [17] state this structure as being able to provide remarkable toughness as well as resistance to the rise and expansion of brittle cracks, thereby contributing to the formation of effectively strengthened coatings [58].

Generally, to summarize the benefits of FCVAD coating method over other methods discussed in this section, the CVD method of coating is characterized by involving high temperatures in the process of coating formation, which induces brittleness in the substrates among other drawbacks and requires lengthy time of deposition than needed by arc PVD for similar coating [59, 60]. Similarly, the conventional arc PVD is commonly criticized for its large droplets formation that adversely affects the quality of coatings at least from hardness point of view and additionally minimizing the adhesive strength [42, 57, 61–64]. Nevertheless, FCVAD technique eradicates such problems ensuring minimum droplets thereby elevating the adhesive property with minimum deposition time. Moreover, it exhibits no brittleness while maintaining improved microhardness which subsequently enhances tool performance [37]. The following section reviews such various techniques of FCVAD versions of coatings which are designed to meet industrial needs and challenges [46].

2.2. Review of Coating Techniques of Filtered Cathodic Vacuum Arc Deposition (FCVAD)

2.2.1. Review of the Coating Techniques. Various techniques of nanocoating have been reported in the last decade by different researchers. The papers reported under FCVAD method of coating described the techniques applied to deposit the coatings on different substrate materials by applying diverse coating materials targeting to deal with machining challenges identified by manufacturing industries.

A typical technique applied under the method of FCVAD setup is done by [7], in an objective to integrate characteristics of carbides and ceramics along with nanoscale coatings, aiming to give a possible remedy to a real scientific problem. This research took into account the existing industrial challenge of difficult cutting conditions containing thermal and mechanical impact on the tool-work interface. The composition of a tool material with functional combination of required properties was framed by this research [7].

This research developed a three-layered architecture of coating called Layered Composite Ceramics (LCC). The three layers of coating consist of carbide underlayer, a ceramic intermediate layer, and nanoscaled multilayered coating (NMC) outer layer. Literature supports the idea of this particular research made by [7] in that enhancement of surface properties of coating and decrease in tendency of brittle fracture are achievable through the outer layer coating of the LCC [7, 65–69].

Looking into the specific technique of ion bombardment on the ceramic layer during FCVAD coating deposition of the outer layer, it was observed to result in the avoidance of surface defects of the ceramics and development of useful compressive stresses. This was found to enhance the curing of the ceramic surface defects, particularly those existing as surface submicrorcracks. Moreover, improvement of adhesion between the coating and the substrate is established by transitional layer [69, 70].

The NMC architecture in this research contained an outer layer with wear resistance characteristics along with an intermediate layer which has nano-sublayers with effects of adhesion of the interfacing layers and thermal barrier characteristics and the underlayer with adhesive properties. The LCC which act as substrates to the NMC were primarily cleaned through chemical ways and mechanical methods prior to FCVAD coating processes. The FCVAD technology applied in this experiment made use of VIT-2 rig which has a filtering device. This helped to minimize the impurities which affect the coating quality [7].

In another research by [37], which made use of the FCVAD method and a VIT-2 rig for controlling the structure of coatings, in order for achieving nanograins and nanosublayers, the research used its own techniques. The first technique applied here was the supply of extra energy to
the deposited coating in a different objective as compared to [12], which was made in an objective of ion embedding into the exterior of the substrate. However, in this case, the research applied extra energy to the already deposited coating in an aim to result in generation of thermal energy on the substrate. Further, this was followed by a very high-speed cooling. The whole technique helps to realize the facilitation of plasma-chemical formations of compounds synthesis while promoting the movement of atoms. In addition to this, the coating centers are grown at the coating-substrate interfaces for enhanced adhesion [37].

An important point to note here is that, in order to regulate the grain dimensions and structure, the energy and intensity of bombarded ions were manipulated through the FCVAD parameters. In this research, the FCVAD process was proven to allow generating a new technology of coating deposition on carbide inserts. The inserts are to be used to reprofile railway wheels. In this technique of coating and the chemical content, the structural arrangement along with the characteristics of the coating elements met the design requirements of various operational challenges during the reprofiling machining process of the work-hardened railway wheels [37].

Paper [37] explained the experimental procedure beginning from the preparation of the samples. The sample preparation of this study involved cleaning and fine cleaning of the samples through ultrasound and flattened, respectively. The setup contains special equipment to locate the samples into the unit VIT-2 rig vacuum chamber. This rig makes use of a mechanism enabling the rotation of the samples in it in a planetary fashion in a range of speeds. In the research, vacuum creation up to 0.01 Pa and further cleaning of the samples were made through bombardment of the sample surfaces with argon or other metal ions. At the final stages of the process, the samples were activated by means of electrons discharge for facilitation of the next coating deposition of Ti-TiN-TiCrAlN [37].

A research by [17] made preliminary investigation to form an NMCC coating to fulfill coating requirements to be made on carbide tools. The study made the standard for the selection of the coatings to be the thermodynamic criterion. Furthermore, to choose the constituent layers of the NMCC coatings, it applied the Hume-Rothery rule. The primary objective of the research by [17] focused at NMCC coating on carbide inserts and to compare the properties like hardness, adhesion to substrate, and cutting parameters of the deposited coatings, with the uncoated carbide inserts [17].

For the coating process, the common type VIT-2 unit was applied. In this unit, coating deposition was possible for substrates with different tool materials. This paper further stated that FCVAD system is free from causing structural changes on the substrate and it rather delivers enhanced adhesive nature at the coating-substrate interface. The research also identified that this system enabled a nicely controlled healing of surface defects on the substrate and generation of residual stresses helpful for effective coating formation. The paper also shows the impact of the energy applied on the coating deposition in the generation of nanoscale grain size as well as formation of sublayer coating thickness [17].

As far as the procedure following the FCVAD coating and the techniques applied in the process is concerned, this research strictly followed similar steps as the previously discussed FCVAD coating method with the usual vacuum arc VIT-2 unit by applying procedures starting from sample preparation to coating deposition [17].

A research by [36], which made use of the VIT-2 unit for deposition of coatings, described this unit as having a lot of improvements compared with the common arc PVD units. The enhancement of this unit used in this research includes the filtration of the microdroplet, the dampening system, the updated rotating table mechanism and the gas supply, among others. The paper described further the details of generation of coating characteristics by appropriate choice of the composition. It also states that increasing the hardness of the material of the coating through alloying has been successful to manage the generation of the characteristics of the coating that enhances tool performance. However, the coating composition remains to be regulated through the VIT-2 unit. Therefore, the composition relies on the quantity of cathodes and their relative location to each other. It also depends on how far the cathodes are placed from the substrate at the time of deposition. In cases of requirements of separate cathodes, planetary rotation of the substrates results in the generation of multilayer structure in a single rotation in a fashion of one after the other deposition of sublayers by including the transition layers between each other [36].

This research reported that manipulation of the VIT-2 unit enables adjustment of the characteristics of the coating. Moreover, the control over layout of VIT-2 has been recognized for enabling the management of mechanical and physical characteristics of the deposit. This research indicated also that the properties of coatings with multiple elements in their composition rely on the constituent elements that make up the cathodes. Moreover, the characteristics of the coatings are also dependent on the constituents of the reaction gases [71].

Technique of coating formation that involves assisting high-energy exposure is also explained by [36]. This technique is elaborated by this paper as a means of generating variations in characteristics of the coatings by applying additional energy to the deposition to generate enhanced property of the tool. This effect was achieved due to the avoidance of residual stresses by the action of laser radiation. The research reported that the effect of pulsed laser action also enabled enhancement of microhardness of the deposit and the adhesive bond of coating-substrate interface. The total effect of such coating was explained by the research to result in reduction in probability of wear of the coated tool.

According to [36], there is also another technique by which formation of an important coating property can be generated in the development of the deposit. This technique brought the desired changes in the characteristics by applying both of the coating deposition and assisted bombarding of the deposit. This ultimately results in enhanced properties of the coatings physically, mechanically, and chemically. Furthermore, manipulation of the energy
supplied and the intensity of bombarding beam of ions enables controlling the grain sizes, resulting in the regulation of required coating parameters \[12, 72\].

The research by \[73\] attempted to resolve the challenges of cutting of parts with high hardness (HRC 55-60) that require increased accuracy of cutting with minimized application of cutting fluids or dry cutting conditions. This research applied nearly the same procedure as \[12\], to mitigate elevated heat exposure to every component of the cutting system during high-speed machining \[73, 74\].

Noting that the metal-working industries had taken major steps in identifying various kinds of cutting ceramic (CC) which do not comprise deficient elements, constitute elevated hardness ranging between HRA 91 and 94 and thermal resistance up to 1450°C, are wear resistive, and are manufactured through comparatively easy and cost-efficient technology \[7, 9, 73\]; the research by \[73\] insists on the need for further improvement to CC for many reasons. The major reasons include the fact that cutting ceramics (CC) are usually known for their low viscosity and resistance to bending, embrittlement, and reduced thermal resistance. This implies that, obviously, a CC tool is highly susceptible to thermal cyclic loads and is very much exposed to brittle damage when prone to contact stresses exceeding the range between 900 and 1000 MPa. That describes the limitation of its application \[7, 9, 71, 73\].

With this understanding of the limitation with CC, \[73\] came up with the idea of enhancing the performance of tools made of CC and extended its application by the deposition of nanoscale multilayer composite coatings (NMCC). With this attempt the study used inserts of ceramic (VOK-200), that is, mixed and layered ceramic with carbide content \[7, 9, 74\]. To obtain these coatings, FCVAD method of deposition by \[73\] applied similar coating techniques, procedures, and equipment as most FCVAD methods of coatings used.

Paper \[75\] discussed aspects of the development of NMCCs formed through application of FCVAD to be applied to the tungsten-free carbides. The paper aimed at improving cutting characteristics of tools thereby increasing its range of application. The basic challenge mentioned by this research which led it to this study was stated to be the minimized fracture toughness and low bending strength, added to reduced thermal conductivity of tungsten-free carbides.

Paper \[75\] further explains the challenge by stating the gap that tungsten-free carbides are found to have restricted application for noncontinuous cutting and cutting of hard-to-machine alloys. In relation to this, this paper reflects the generation of NMCCs to create a balance of hardness versus toughness. Paper \[75\] claims for developing an architecture with three layers, of which each layer contributes its own function in the coating rendering the total effect of the coating objectives. Consequently, the deposited coating was reported to enhance the machining properties of tungsten-free carbides. This has in effect widened the capability range of application by comfortably machining the heat-treated and hardened steels as well as thermally resistive carbides \[75\].

This research applied a technique which is similar to the previously stated researches specifically by making use of NMCC coating in a vacuum arc VIT-2 unit. During the preparation process, cleaning the working part of the inserts was chosen to be by argon ions at high pressure in a range of 1.5 up to 2.5 Pa. Following this, the ultimate cleaning and activation process of the inserts took place in non-self-maintained gas discharge \[75\].

The NMCCs formed in this case have revealed that the nitrogen content in the NMCC formed was observed to be determined by the reaction gas pressure and by the energy of ions. Therefore, the process parameters have a strong impact on the structure, composition, and many other performance characteristics of the coating \[75\].

The method analysis applied to generate functional coatings over ceramic blade tool was studied by \[76\]. The study mentioned the previous effort made by making use of Physical Vapor Deposition \[77\]. As it is commonly known, deposition of coatings for ceramic blade tool was founded on the properties of physical, mechanical, and thermal conditions. It is obvious that the basic properties of ceramic exhibit various undesired properties like highly reduced thermal conductivity, high resistivity to electricity, and high exposure to defects at subsurface caused by the production process. Hence, in order to minimize or eliminate such and similar challenges and to achieve an improved effect on the ceramic tool, the research by \[76\] applied the FCVAD process at VIT-2 unit \[78, 79\]. This research was made on Al₂O₃-TiC which has very wide application in modern manufacturing.

The other research by \[80\] also applied thermodynamic criteria as seen above under the research by \[17\], to assess the composition of NMCC. In this research also the FCVAD technology was developed again as a method to enhance the cutting characteristics of ceramic tools. The research passed through the usual, primary processing of cleaning followed by the deposition of Ti-TiAlN-ZrN/TiAlN coating of NMCC structure. This deposition was made on Al₂O₃, Al₂O₃-TiC, and Si₃N₄, tools which were the focus of the research \[75\].

In another similar research by \[81\], which used the same coating method and technique, the deposition was made by using \((85\%Zr + 15\%Nb)\) cathode, 99.8% Ti cathode, and 99.8% Al cathode including filtering of the ions in forming NMCC of Ti-Tin-(9bZrAl)ₐn basis.

The research by \[82\] had a minor modification on the technique of the coating process on carbide tool inserts. The VIT-2 unit contained evaporators which are three in number. The two of them were cathodes of Ti, which was aimed for stabilizing the electromagnetic property of the cathode and in the meantime the plasma of ion flow too. The remaining evaporator was Al cathode which has filtering equipment for droplets of ion in addition to the accelerating task on the ion flow \[82\].

After this setup, the research describes the preliminary preparations taking place before the deposition of the coatings. Based on this, the substrates were mounted in the VIT-2 unit equipped with a table mechanism enabling rotating the carbide inserts through the flowing plasma of ions. It also states the creation of the residual pressure within the unit was under automatic control and electronically
regulating system for effective deposition. Ultimately, the coating deposition of Ti-TiN-TiAlN on the cutting surface of carbide substrates passed through similar procedures including the common stages, from precleaning accompanied by washing, to the synthesis of the coating layers in a sequential manner. This research has indicated that the significant parameters of FCVAD method determining the characteristics of the coating to be formed are the control of arc current of the cathode specifically (the titanium), the control of nitrogen gas pressure of the chamber, and the control of voltage supply to the substrate [82].

In another research, impact of composition and coating architecture of NMCC on the effective working life of carbide tools was investigated by [83]. The coatings were made in a VIT-2 unit of FCVAD setup, while the testing of the coating deposited was made through turning operation in the longitudinal direction [84].

The research made its experiment on the basis of previous experiences specifically on coatings made in a purpose to resist wear in machining process performed on stainless steel. The coatings selected for the research included aluminum and niobium, where with fine tuning of these compositions of the coating, the mechanical properties of the coatings exhibit significant change. On this basis, the increase in aluminum was observed to increase hardness in addition to wear resistance. Moreover, the increase in niobium was found to increase the impact toughness along with the resistance to heat. On the other hand, the research by [83] explains that (Zr,Nb)N-(Cr,Zr,Nb,Al)N deposit exhibits the required hardness and crack resistance. These properties are considered to be fairly balanced in the coating. However, the paper further elaborates that an increment in fraction of zirconium will have an impact of reduction in the probability of diffusion of coating elements with chromium content when cutting chromium alloy workpiece [83].

Paper [85] made its research by making tools with an improved nanostructured coatings with additional characteristics of wear resistance. The nanostructured wear resistant coatings (NWC) are formed by the FCVAD method of coating. The research indicated that it applied a plasma duct, to be applied in the filtering of macro/microdroplets, which makes it unique from the researches reviewed in this paper. This duct, special in its structure, is secluded from the chamber. This research presented the impact of controlling the parameters on the output of the coated tools. The research accompanied the results of the topological investigation of the coatings along the result of the hardness and compared it to the standard PVD coatings [85].

Literature indicate that principal manufacturers of coated tools make use of numerous basically different methods for deposition. However, each method of deposition is observed to have its own advantages and disadvantages [10, 12, 86–92]. As far as methods of arc PVD are concerned, they are progressively applied in production of cutting tools. Paper [85] also stated the commonly mentioned limitation of the arc PVD technique which is the vapor-ion flow that comprises a small amount of melted microdroplets from the cathode and solid fragments [85].

The circumstances under which erosion of the cathode surface takes place, including the consistency and steadiness, are crucial in the process. The research elaborates the varying situation of the erosion process happening on the cathode is controlled by the static magnetic fields in the system. The erosion, as described by [85], happens in stochastic fashion being controlled by certain law. However, in this research, it is reported that controlled arc is applied resulting in balanced consumption of the cathode [86–90].

The research by [40] began with sample preparation which involves as usual ultrasonic cleaning by applying appropriate detergent. The samples are further washed, rinsed, and finally cleaned with beam of plasma in the chamber. After this preliminary preparation the samples are coated with three-layered Zr-ZrN-(Zr,AlSi)N composition in VIT-2 unit through FCVAD process. Various comparisons and tests are conducted, among which measuring the microhardness and microstructure analysis to identify delamination, wear, and failure conditions are a few [40, 93].

In a bit differing scenario, the development of a unique FCVAD system which is called AFCVAD was reported by [12]. This system involves the technique of applying assisting impulse for the deposition process on cutting tools. As it is common in cases of all FCVAD methods, to form wear resistance coating (WRC), the procedure to form assisted vacuum arc deposition also contains the facility for filtration of condensate from microdroplet components. However, in the case of AFCVAD, this is implemented in a different unit called arc installation unit VIT-3 [12, 49, 94, 95], unlike other FCVAD methods which make use of VIT-2 unit. Focusing on the technique applied in this research, in conducting the experimental studies, [12] used the station VIT-3 for the AFCVAD process to take place [49, 94–96]. This installation, being unique from the well-known installation unit VIT-2, is furnished with evaporators capable of stabilizing and filtering of micro/macrodroplets of ions. Furthermore, it is also provided with equipment of voltage supply to the arc implanter. In this system, the coating technique allows deposition of the coatings on the substrates at about 160°C [12, 49].

In AFCVAD process, the deposited material is further bombarded by high-energy ions by making use of an implanter. Consequently, these processes lead to radical enhancement of the wear resistance layer due to the improvement generated on the structure of the coating. The improvements include high density of coating along with high strength adhesion at the tool coating interface. It was also found to minimize the sizes of grains of the coating materials that results in the enhancement of hardness along with sufficient ductility as a result of the generated nano-structure [12].

Finally, the research by [97] used coating techniques which are somewhat different from the previously mentioned techniques, in an objective to create an improved life of carbide inserts by depositing a composite coating with a nature of wear resistant property and a complex structure on the surface of the carbide insert. This is made through surface treatment of comprehensive nature which involves chemical as well as thermal handling. The technique to
develop the comprehensive treatment on the carbide surface also includes nanocoating and an effect of resisting wear challenges in the process of machining [97].

Unlike the other researches previously mentioned, in cases of this technique, the preliminary action is deposition of thin films of Nb70Hf22Ti8 base. The coating thicknesses range between 150 nm and 250 nm. Application of high-current beam of electrons in the unit chamber was realized for the synthesis of the layers for effective deposition. The unit which entertains these actions is different from the units in the previously discussed cases of researches. This unit is known as “RITM-SP unit” and takes a vacuum chamber having an energy source with current of increased intensity beams along with a double spraying magnetron. The research indicated that this unit is capable of coating films on different tool materials. The coating deposited is further stirred along with the substrate through high intensity beam of electrons [98].

The treatment ultimately results in the enhancement of plastic nature as well as thermal conduction of the surface of the carbide insert. Therefore, alloying took place with hafnium carbide within the structure of composite carbide over its surface. Hence, the complex coating generated in multiple layers as a composite deposition wear resistive coating was established on (TiAl)N basis. This deposition was made in a unique unit called "Platit Pi 80", applying a mechanism involving the rotation of the cathodes in a lateral fashion through a technology called “LARC” [98].

2.2.2. Synthesis of the Reviewed Coating Techniques. The above discussion on the review of the various techniques of coating under the FCVAD method is summarized in Table 1 for succinct reference to the reader. The installation units, being fundamental for the coating technique applied, influence the quality and effectiveness of the final coating generated in the process. Hence, this summary made clear the four different installation units applied by the different writers considered under this review. These units are the VIT-2 installation unit, which was commonly applied by most of the reviewed papers, the vacuum arc installation unit VIT-3, which is not yet widely used by many researchers and it is observed to be applied in relation to the new AFCVAD technique of coating, the RITM-SP unit which was applied on the carbide substrate with surface film followed by liquid-phase stirring of the film with strong pulsed electron beam in a vacuum chamber, and the Platit Pi 80 unit which applies LARC (lateral rotating cathodes) technique for the deposition of the multilayered complex composite WRC coating which is made after the treatment of the carbide substrate.

2.2.3. Summary of the FCVAD Techniques. Generally, in this review it is observed that the FCVAD techniques of coating primarily begin with sample preparation. The sample preparation stage involves mainly cleaning and preheating the substrate as part of enhancing the effectiveness of the coating. At the cleaning step, chemical fluid cleaning which is made mainly through ultrasonic vibration is performed. This stage is a preliminary step usually done before the nanocoating and includes cleaning through washing, rinsing, and drying [17, 37, 73, 80, 82].

The ultrasonic cleaning might be followed by washing with distilled water, fine cleaning with flannel, or rubbing with high-octane gasoline. Following this, usually, final sample cleaning in gaseous plasma from the glow discharge is performed. This is ionic cleaning which, in the meantime, heals defects of the tool surfaces and simultaneously creates thermal activation for the succeeding nanocoating process [17, 37, 40, 80, 82]. Finally, this sample preparation stage is accomplished by sequential synthesis of layers of the nanocoating [82].

The major techniques involved in FCVAD method after the sample preparation stage include preparation of cathodes from the constituents of the coating materials. The number of cathodes employed varies depending on the number and types of the coating materials required in the deposition process.

The FCVAD technique facilities setup and commonly contains modern vacuum arc stations with controlled arc which is applied in all types of the installation units for the purpose of controlling the coating parameters. The schematic diagram of the FCVAD facility setup is indicated in Figure 1 below. In some of the cases like the assisted filtered cathodic vacuum arc deposition (AFCVAD), in which surface films are deposited prior to the nanocoating, treatment of the film by means of pulsed laser radiation is made [54].

To sum up, the techniques in FCVAD setup involve cleaning and thermal activation of the substrates to be coated through application of a variety of approaches and preparation of cathodes. Finally, setting up of the whole installation units based on the required coating parameters and locating the substrate in the chamber make it ready for the coating deposition.

2.2.4. Summary of the Merits of Various FCVAD Techniques. The techniques applied in FCVAD process to deposit NMCC are identified to be diversified with each diversity adding up its own merit compared to the preceding coating technique. The variety of the techniques applied in FCVAD process is demonstrated by the working principles and series of enhancements made on the respective vacuum arc installation units. The installation units, being fundamental for the coating techniques, influence the quality and effectiveness of the final coating generated in the process. Hence, this summary sorted out four different installation units applied to generate different techniques of coating by different researches covered under this review. The first and the most common unit which has been applied by most of the researches reviewed under this paper is the VIT-2 installation unit. This unit is considered to be the evolved form of the standard arc PVD unit which brought about substantial enhancements on the coating generated. The merits and comparative additional capabilities delivered by this unit include filtration of the microdroplets of the plasma gas beam, microarc dampening,
**Table 1: Synthesis of the coating techniques reviewed.**

| S.N | Paper | Sample preparation technique | Coating sys. installation | Coating technique applied |
|-----|-------|------------------------------|---------------------------|---------------------------|
| 1   | [7]   | (i) Preparation of LCC with NMC coating was made  
     (ii) Chemical and mechanical treatment of the LCC substrates before deposition | VIT-2 installation unit | (i) Development of LCC on a carbide tool base, a ceramic intermediate layer, and NMC outer layer  
     (ii) The LCC is developed by  
     (i) hot pressing  
     (ii) hydrostatical condensation  
     (iii) gas-static compacting of the material  
     (iii) FCVAD technique applied to develop the NMC |
| 2   | [12]  | (i) For the application of WRC, ultrasonic washing, drying  
     (ii) Rubbing with high-octane gasoline and cooling the samples in the chamber  
     (iii) Locating samples on VIT-3 station table  
     (iv) Devacuumizing of the station, cooling of the samples  
     (v) Planetary movement of the samples in the coating process  
     (vi) Vacuumizing the chamber to 0.01 Pa pressure  
     (vii) Fine cleaning inserts surface  
     (viii) The characteristics of WRC formed were studied | Vacuum arc installation VIT-3 unit | (i) Development of coating surfaces on cutting tools through ion flow assisted by constant exposure to energetic ions  
     (ii) Wear resistant complexes (WRC) are developed  
     (iii) To form WRC, arc deposition with filtration is applied  
     (iv) Characteristics of WRC like thickness, adhesion, morphology |
| 3   | [17]  | (i) Washing the carbide inserts with chemical fluid through ultrasonic vibration  
     (ii) Samples activated thermally with electrons from glow discharge | VIT-2 unit | (i) Preliminary studies to form the NMCC (through thermodynamic criterion “Gibb’s energy”)  
     (ii) Furthermore, for choosing composition of coating Hume-Rothery rule was applied |
| 4   | [36]  | (i) Not specified | VIT-2 vacuum arc unit | (i) Coating formation using a pulsed laser  
     (ii) Reducing residual stress and increasing microhardness of the coatings  
     (iii) Testing of the coated tools |
| 5   | [37]  | (i) Preliminary chemical activation cleaning by ultrasound, fine cleaning with flannel  
     (ii) Vacuum was created for samples  
     (iii) Fine cleaning through argon or metal ions | VIT-2 rig | (i) Nanocoatings deposited on tools for rough reprofiling of railway wheels sets  
     (ii) The coatings were formed using FCVAD  
     (iii) Additional supplied energy to the deposited coating to create thermal energy |
| 6   | [40]  | (i) Primarily, the samples were cleaned by ultrasonic cleaner  
     (ii) Then, washed in distilled water  
     (iii) Final sample cleaning in gaseous plasma | VIT-2 unit | (i) Cathodes of different compositions of zr, Al, and Si were prepared  
     (ii) 4 samples of Zr-ZrN-(Zr,Al,Si)N coatings deposited with different deposition duration  
     (iii) 2 Zr cathodes and 1 (Al,Si) cathode applied at a time  
     (iv) The cathodes were installed in evaporators |
| 7   | [73]  | (i) Prewashing of ceramic tool CI with ultrasonic vibration  
     (ii) Ionic cleaning of CI with ions of Ar or metal  
     (iii) Thermoactivation of tool samples | The installation VIT-2 (producer STANKIN-VNIITS) | Formation of NMCC on the surfaces of CI made of CC and LHC |
| 8   | [75]  | (i) Plasma cleaning of the inserts by Ar ions  
     (ii) Final cleaning and thermal activation | Vacuum arc VIT-2 unit | NMCCs were formed on tungsten-free carbides  
     (i) Applying arc PVD and its innovative version FCVAD |
| S.N | Paper | Sample preparation technique | Coating sys. installation | Coating technique applied                                                                 |
|-----|-------|-------------------------------|---------------------------|------------------------------------------------------------------------------------------|
| 9   | [76]  | (i) Not specified              | VIT-2 rig                 | (i) Filtered vacuum arc deposition is major technique applied  
(ii) Tool of popular mixed ceramic  
(iii) Cutting properties of the ceramic tools were studied |
|     |       | (i) A primary process of sample preparation with ultrasonic cleaning, rinsing, etc. is made on the ceramic substrate |                         | (i) Used thermodynamic criteria to assess the composition of coating  
(ii) The inserts are given a planetary motion in the VIT-2 unit, for uniform thickness  
(iii) Microstructural research and chemical analysis done  
(iv) Ti-TiAlN-ZrNbTiAlN NMCC coating deposited on ceramic substrates |
| 10  | [80]  | (ii) The techniques through the VIT-2 unit involve further ion cleaning for surface healing | VIT-2 unit | |
| 11  | [81]  | (i) Not specified              | The VIT-2 unit            | (i) Studies of adhesion characteristics and wear and failure pattern of NMCC is made  
(ii) Deposition through fused cathode on standard arc evaporators and cathode 99.8% Al  
(iii) Cutting properties of the coated versus the uncoated tool and a referent coating TiN tool is studied in turning of steel C45 |
|     |       | (i) Primary cleaning and washing  
(ii) Samples loading on the chamber  
(iii) Vacuum pumping  
(iv) Ion cleaning with thermal activation of samples  
(v) Sequential synthesis of layers |                         | (i) Three evaporators employed; two equipped cathodes of Ti, one with a cathode of Al  
(ii) The systems with Al contain filter  
(iii) Residual pressure is systematically controlled |
| 12  | [82]  | (i) Preliminary formation of coatings on carbide substrates  
(ii) Treatment of the substrates with surface films Nb70Hf22Ti8 | The VIT-2 unit | (i) The deposition of films in RITM-SP unit on samples, followed by electron beam stirring of film and substrate  
(ii) Followed by, NMCC coatings of (TiAl)N  
(iii) Microstructural tests on the samples are also made |
| 13  | [97]  | (i) Heating and cleaning the products of gaseous plasma  
(ii) Pumping and heating the chamber  
(iv) Deposition of coating and cooling of products | RITM-SP unit and A unit Platit Pi 80 applying lateral rotating cathodes | (i) Nanostructured wear resistant coatings of - TiN  
(i) Ti-TiN-(Ti,Al)N  
(ii) (Zr,Nb)N-(Cr,Zr,Nb,Al)N  
(iii) (Zr,Nb)N-(Zr,Al,Nb)N are deposited  
(i) Microstructure, hardness  
(ii) Adhesion strength in the coating-substrate system  
(iii) Chemical compositions were analyzed  
(ii) Turning of austenitic stainless steels AISI 321 and S31600 by the coated tool |
| 14  | [83]  | (i) Not specified              | VIT-2 unit applied        | (i) Modern vacuum arc stations with controlled arc are applied  
(ii) There exists combustion stability  
(iii) Absolute uniform electron-erosion of the cathode  
(iv) Study of properties of NWC |
| 15  | [85]  | (i) Heating and cleaning the products of gaseous plasma  
(ii) Pumping and heating the chamber  
(iv) Deposition of coating and cooling of products | VIT-2 unit with special plasma duct separated from the chamber | (i) The Hume-Rothery rule was applied to determine the coating composition  
(ii) The VIT-2 unit with arc evaporator  
(iii) Uncoated and coated carbide tool with TiN, deposited to compare tool life  
(iv) Microstructural studies of hardness, adhesion, etc. are performed |
| 16  | [72]  | (i) Heating and cleaning the products of gaseous plasma  
(ii) Pumping and heating the chamber  
(iv) Deposition of coating and cooling of products | VIT-2 unit | (i) The Hume-Rothery rule was applied to determine the coating composition  
(ii) The VIT-2 unit with arc evaporator  
(iii) Uncoated and coated carbide tool with TiN, deposited to compare tool life  
(iv) Microstructural studies of hardness, adhesion, etc. are performed |
enhanced rotating substrate stand, and dynamic gas provision scheme [36].

In the FCVAD installation units including VIT-2 unit, additional supplied energy to the deposited coating is made to create thermal energy which is followed by rapid cooling which contributes for the creation of nanolevel grains in the coating structure as well as nanosublayers of coatings. This is an important part of the enhancement on the coating quality of the FCVAD coatings as compared to the CVD and PVD coatings.

The second installation unit is the vacuum arc VIT-3 unit, which is not yet widely applied and is observed to be practiced in relation to the new assisted filtered cathodic vacuum arc deposition (AFCVAD) technique of coating. This unit further incorporates arc evaporators along with magnetic stabilizers to make a further enhancement to the VIT-2 installation unit coating technique. This unit is equipped uniquely with implanter unlike the VIT-2 unit. The implanter plays an important role in enhancing the coating-substrate adhesion through high-energy beams of ions supplied by the implanter on the coating, affecting the underlayer of the multilayer coating through partial ion implantation at the coating-substrate interface [12]. In AFCVAD, in which surface films are deposited prior to the nanocoating, treatment of the film by means of pulsed laser radiation is made to reduce residual stresses and enhance the microhardness and adhesion of the coating-substrate interface [54].

The third type installation unit is the Platit Pi 80 unit which applies LARC (lateral rotating cathodes) technique for the deposition of the multilayered complex composite wear resistant coating (WRC), which is made after the treatment of the carbide substrate with surface film. Before the WRC coating is generated, the fourth type of unit, called ‘RITM-SP unit’, is applied for the formation of a preliminary treatment of the substrate with surface film. The subsequent liquid-phase stirring of the film with strong pulsed electron beam in a vacuum chamber results in the alteration of the phase structure of the substrate. This in turn facilitates a dramatic increment of contact area and consequently high carbide formation reaction that enhances the coating-substrate adhesion [97].

Generally, these four types of installation units have made a great contribution for enhancement of the state-of-the-art coating technology through FCVAD setup delivering numerous merits over CVD, PVD, and other types of coatings [37].

### Table 1: Continued.

| S.N | Paper | Sample preparation technique | Coating sys. installation | Coating technique applied |
|-----|-------|-----------------------------|---------------------------|--------------------------|
| 17  | [99]  | Primarily, comparative wear resistance tests carried out at cutting of steel 9SiMn16 | No unit specified for the NMCC coating applied | (i) CNC lathe index GU 600 applied for machining (ii) Cutting forces measured with force dynamometer (Kistler type 9121) (iii) A raster electron microscope FEI quanta 600 FEG applied for microstructural studies on NMCC coated carbides |

The different coating materials applied to the substrate materials on which the coatings were applied and the work materials which are machined by using the developed coated tools were synthesized under Table 2. This summary indicates that most coating materials are chosen based on previous experiences of research and industry. However, the structures of the coatings applied vary based on the objective aimed by the research to solve specific cases of challenges in the machining process. Furthermore, the work materials, which the coated tools are supposed to machine, are generally materials which are hard to machine among which some are real industrial challenges which pose problem of tool life and hence exacerbate cost of machining of the products.

### 2.2.6. Summary of the Coating Materials.

Primarily, the coating materials composition for NMCC is to be selected based on the underlying thermodynamic principles and the laws of tribology. Thermodynamic standard described by Gibbs energy considers the interatomic spacing between the coating and the substrate and between the material to be machined and the outer layer of the NMCC.

Through this, it is possible to formulate general requirements for coating materials of the cutting tools [17]. Further, the multilayer architecture is designed on the basis...
of the Hume-Rothery rule which considers the discrepancy of atomic sizes of joining compounds.

To summarize the coating materials commonly applied in NMCC coating covered under this review, Ti, Zr, and Cr are the most popular coating materials used as underlayer of the three-layered NMCC coatings. However, their nitride variants TiN, CrN, and ZrN are also used similarly at the interfaces of the NMCC coating and the substrates favoring the required adhesion between the coatings and the substrates [17].

However, TiN, CrN, and ZrN are mostly used as intermediate layer of the NMCC, providing adhesion to the underlayer and the outer layer to maintain integrated multilayer NMCC coating. CrAlN and TiAlN are also used as intermediate layer coating materials in some cases, though they are mostly used as outer layers of the multilayer coating architecture [17].

It is observed under this review that the materials for outer layer coatings of NMCC have wider options. Accordingly, TiCrAlN, (ZrCrAl)N, (ZrCrAl)N, (NbZrTiAl)N,

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Table 2: Synthesis of the coating materials, substrate, and work materials of the reviewed papers.

| S.N | Paper | Coating material | Substrate material | Material to be machined |
|-----|-------|------------------|--------------------|------------------------|
| 1   | [7]   | LCC with Ti-TiN-TiCrAlN and Zr-ZrCrN-CrN | Carbide VK6-M carbide VK6-M-TiAlN VOK-71, VOK-71-TiAlN, LCC, LCC-NMC (on the basis Zr-ZrCrN-CrN) LCC-NMC (on the basis Ti-TiN-TiCrAlN) | Workpieces of hardened steel and hard-to-machine alloys |
| 2   | [12]  | Ti-TiN/AlN-TiCrAlN, Zr-ZrN/AlN-ZrCrAlN | Carbide inserts | Structural steels and heat resistant alloys, turning of nickel alloy HN77TUR |
| 3   | [17]  | TiN (as a “referent” coating for tests), Ti-TiN-(TiCrAl)N, Zr-ZrN-(TiCrAl)N, Cr-CrN-(TiCrAl)N N,-Ti-TiN-(NbZrTi)N,-Ti-TiN-(NbZrAl)N,-Ti-TiN-(NbZrTiAl)N,-Zr-ZrN-(ZrNbCrAl)N, and Cr-CrAlN-(ZrZrCrAl)N | Carbide cutting tools of carbide (WC+15%TiC+6%Co) of SNUM form (ISO) | The longitudinal turning of steel |
| 4   | [36]  | TiN-TiAIN,TiN-TiZrN,TiN-TiAIN-(TiZrTi)N, and Ti-TiN-(TiZrTi)N | Inserts of cemented carbides | Steel C45, steel 41, CrMo4DIN(HB230), steel AISI, 321(HB 180), steel AISI L6 (HB 240) |
| 5   | [37]  | the intermediate layer; Ti-N, Cr-N, Ti-Al-N, Ti-Cr-N, Ti-Cr-Al-N, and Ti-TiN-TiCrAlN | Carbide inserts type P30 | Work-hardened surface of railway wheel-sets |
| 6   | [40]  | Zr-ZrN-(Zr,Al,Si)N | Various carbide tool materials | Not applicable |
| 7   | [73]  | Ti-(Ti,Al)N-(Ti,Cr,Al,N) (Ti,TiN-Ni,Al, Zr,Nb,Nb,Cr,N) | Inserts (Cl) made of mixed ceramic VOK-200 | Hardened steel |
| 8   | [75]  | Ti-(Ti,Al)N-(Ti,Cr,Al,N) | Tungsten-free carbide | Chromium-based heat resistant alloy, heat-treated steels of increased hardness |
| 9   | [76]  | Ti-(Ti,Al)N-(TiCrAl)N compared with coating Ti-(TiAl)N-ZrN | Ceramic (Al_{2}O_{3}-TiC) | Steels, hardness of HRC > 52 |
| 10  | [80]  | The Ti-TiAIN-ZrNbTiAIN coating structure | Ceramic; Al_{2}O_{3}, Al_{2}O_{3}-TiC, and S_{i}N_{4} | Hardened steel |
| 11  | [81]  | NMCC coating of Ti-TiN-(NbZrAl)N | Carbide tool | Steel C45 |
| 12  | [82]  | Ti-TiAIN coatings | Carbide tools | (P10-P20) steel |
| 13  | [97]  | Preliminary formation of films on the basis of composition Nb_{0.3}H_{2}_{9}Ti_{0} multilayered coating on (TiAl)N basis | Carbide tools | Steel C45 (HB 200) |
| 14  | [83]  | (Zr,Nb)N-(Zr,Al,Nb)N | Carbide tools | Austenitic steel, type 16Cr-10NI, stainless steels AISI 321, and S31600 |
| 15  | [85]  | NWC Ti-TiN-TiCrAlN and NWC TiAlN-ZrNbN-CrN | Carbide inserts ISO SNUM | Steel C45 (HB 200) and NiCr20TiAl |
| 16  | [72]  | (NMCC Zr-ZrN(Nb,Zr,Ti,Al,N)), and (NMCC Ti-TiN-(TiAl)N) | Carbide tools | Steel C45 (HB 200) |
| 17  | [99]  | Ti-TiN-(TiCrAl)N and Zr-ZrN-ZrNbCrAlN | Carbide inserts SNGN 120412, of various brands | Steel 9Si Mn 16 |
(NbZrCrAl)N, (Zr,Al,Si)N, ZrCrAlN, TiZrAlSiN, (NbZrAl)N, and (NbZrAl)N are the coating materials most commonly used as wear resistant and/or heat resistant outer layers of the NMCC [17].

2.2.7. Summary of the Microstructure of NMCC. Various researches focused on analysis of the microstructure of nanostructured multilayer composite coatings, which have identified the differences among the microstructures of the FCVAD generated NMCC coatings with respect to coatings generated by other methods [37]. Figure 2 shows the microdroplets formed in arc PVD coating compared with FCVAD coating. In this figure, the SEM micrographs clearly indicate the concentration of the microdroplets. As can be seen obviously, the microdroplets in the arc PVD coating are larger in size and plenty in number whereas in the FCVAD coating they are few in number and smaller in size. This shows the effect of the filter facility installed in the FCVAD setup which reduces the microdroplets passing to the coating to a level of less than ten percent [37].

Figure 2: SEM micrographs of coated surfaces: (a) standard arc PVD; (b) FCVAD technology [37].

For microstructural analysis, SEM is commonly applied in the reviewed papers to observe and identify the multilayer coating architecture, the wear nature of the coated and uncoated tools, thickness of each layers and sublayers of nanolevel thicknesses (shown in Figure 3), and the crack orientation, by comparing coatings like arc PVD and CVD with respect to the NMCC coating [17].

Identification of micro- and macrodroplets in the various methods of coatings and their effect as a starting point for cracks in the coating is usually observed in the microstructure analysis as shown in Figure 4 below.

Toolmaker’s microscope MBS-10 is applied to observe the wear of the coated tools while scratch testing of the coatings was made for the investigation of the adhesion of the coatings with the substrate by using Nanovea scratch-tester [99].

2.2.8. Summary of Application of the Nanocoatings on Cutting Tools. In this review, it is observed that the application of FCVAD methods of coatings and the
generation of NMCC is observed to be specifically limited only to turning tools. Furthermore, the NMCC coatings are generated only on cutting inserts of turning tools that are made of various tool materials. The substrates on which the nanocoatings are deposited have different material compositions. Generally, the nanocoatings were made on carbide tool substrates. However, there are a variety of other substrates on which the nanocoatings were deposited. Among them are tungsten-free carbides, popular mixed ceramics, and other ceramic substrates. In some cases, before the NMCC coating is made other coatings are applied as under layers. For instance, in the case of [7], before the nanocoating layer is deposited, a carbide layered composite ceramic was initially deposited followed by a ceramic intermediate layer which collectively form a three-layered coating. There are also cases in which ceramic inserts (CI), layered high strength ceramics (LHC), and cutting ceramics (CC) were used as substrate materials for deposition of NMCC, through FCVAD techniques [7].

3. Future Work

Having noticed the output of the review, from the new techniques of deposition of coatings on metal cutting tools, one can identify a gap which can be further explored. Accordingly, the technique of coating revealed by [12] is worth taking attention to be further applied on different substrate material and coating composition to investigate the width of applicability and take advantage of the unique adhesive capacity generated in the coating-substrate interface. In addition to this the new concept of multilayered hierarchical coating shall be investigated to test the enhancement of adhesion among sublayers of the coatings. If a continuous transition like a hierarchy in the structure of the multilayered coating is made, the adhesive force among the coating layers can well be improved [14, 100].

Paper [14] stated that the hierarchical structure comprises a multilayered deposit between 2 or more coating materials, and individual layers might have a various measure of thicknesses. According to this paper, with different numbers of layers and thickness of the coating, this hierarchical structure is identified to deliver inspiring outputs with regard to wear resistance and coating strength. This has been explained comparatively with single layer coating and even multilayered coating of the common type. Moreover, the paper witnessed that hierarchical coatings are not well addressed in researches. Hence, it is suggested by the paper that particularly in fields of cutting tools the impact of hierarchical structure coating is a research gap which shall be further investigated [14, 100].

4. Conclusive Summary

From this review, there are lots of multidirectional lessons learnt. From view point of techniques of coating, it is learnt that there is the emergence of new coating techniques which enhanced the adhesion property between the coating and the substrate material through high-energy ions implanting. Moreover, it is also pointed out how the properties of multilayer coatings can be enhanced through the introduction of a multilayered hierarchical coating. This has been observed to enable an increase in the wear strength due to the coating structure and it has also been identified that the hierarchical coating structure provides protection against crack propagation. On the other hand, the review also has assessed substrate materials on which the coatings are to be made. Based on this, carbide tools, which have a wide coverage in the machining industry, are observed in the reviewed papers to achieve wear resistant coatings of modern generation. This review has also revealed lots of coating material selections based on the requirements demanded by the machining processes applied in the manufacturing of the products and the functional application of the final product. Moreover, different types of real application focused work materials including hardened and difficult-to-machine materials were addressed in the researches covered by this review as objects to be machined by multilayered nanostructured composite coated tools. However, it is found out that there are different techniques of coatings like high-energy ion assisted coating depositions and multilayered hierarchical coating which are not sufficiently researched in this field of study.
Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] M. Sokovic, J. Kopac, L. A. Dobrzanski, J. Mikula, K. Golombek, and D. Pakula, “Cutting characteristics of PVD and CVD - coated ceramic tool inserts,” Tribol. Ind., vol. 28, no. 1-2, pp. 3–8, 2006.
[2] S. Y. Ezugwu, J. Bonney, R. B. D Silva, and A. R. Machado, “Evaluation of the performance of different nano-ceramic tool grades when machining nickel-base, inconel 718, alloy,” Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 26, no. 1, pp. 12–16, 2004.
[3] A. S. Vereschaka, Working Capacity of the Cutting Tool with Wear Resistant Coatings, p. 336, 1993.
[4] S. N. Grigoriev, A. A. Vereschaka, and A. A. Kutin, “Cutting tools made of layered composite ceramics with nano-scale multilayered coatings,” Procedia CIRP, vol. 1, no. 1, pp. 301-306, 2012.
[5] L. D. A. S. Vereschchaka and O. I. Obrezkov, “Development of technology for the synthesis of vacuum arc coating assisting by a high-energy ions,” Proc. Int. Sci. Conf. “Protecto2”, vol. 139, 2002.
[6] A. A. Vereschaka, “Improvement of working efficiency of cutting tools by modifying its surface properties by application of wear-resistant complexes,” Advanced Materials Research, vol. 712-715, pp. 347–351, 2013.
[7] Y.-K. Joo, S.-H. Zhang, J.-H. Yoon, and T.-Y. Cho, “Optimization of the adhesion strength of arc ion plating TiAlN films by the taguchi method,” Materials, vol. 2, no. 2, pp. 699–709, 2009.
[8] A. A. Vereschaka, “Development of assisted filtered cathodic vacuum arc deposition of nano-dispersed multi-layered composite coatings on cutting tools,” Key Engineering Materials, vol. 581, pp. 62–67, 2014.
[9] A. A. Vereschaka, “Methodology of formation of multi-layered coatings for carbide cutting tools,” Mechanics & Industry, vol. 17, no. 7, p. 706, 2016.
[13] M. Narasimha, K. Sridhar, R. Reji Kumar, and A. Aemro Kassie, “Improving cutting tool life: a review,” International Journal of Engineering Research and Development, vol. 7, no. 1, pp. 2278–2367, 2013.
[14] A. V. Mikhailov, I. A. Korolyov, and A. O. Lopatiuk, “Corrosion stability of cutting tool’s material for exploitation of peat deposits,” Procedia Engineering, vol. 206, pp. 668–675, 2017.
[15] J. A. Syed, S. Tang, and X. Menggp, 1–17, 2017.
[16] R. Article and S. K. Mishra, “Toughening of nanocomposite hard coatings,” Advanced Materials Science, vol. 59, pp. 553–585, 2020.
[17] H. Holleck, “Basic principles of specific applications of ceramic materials as protective layers,” Surface and Coatings Technology, vol. 43, no. 5, pp. 245–258, 1990.
[18] V. S. H. Holleck, “Multilayer PVD coatings for wear protection,” Surface and Coatings Technology, vol. 76–77, pp. 328–336, 1995, Part 1.
[19] M. Fallqvist, “Microstructural, Mechanical and Tribological Characterisation of CVD and PVD Coating for Metal Cutting Application,” 2012, https://www.diva-portal.org/smash/get/diva2:516909/FULLTEXT01.pdf.
[20] H. Fukui, “Evolutional history of coating technologies for cemented carbide inserts - chemical vapor deposition and physical vapor deposition,” SEI Technical Review, vol. 82, pp. 39–45, 2016.
[21] L. Zukowska, J. Mikula, M. Staszuks, and M. Muszyfagastaszkuz, “Structure and properties of PVD coatings deposited on cermets,” Archives of Metallurgy and Materials, vol. 60, no. 2, pp. 727–733, 2015.
[22] O. Oluwatosin Abegunde, E. T. Akinlabi, E. Titilayo Akinlabi, O. Philip Oladijo, S. Akinlabi, and A. Uchenna Ude, “Overview of thin film deposition techniques,” AIMS Materials Science, vol. 6, no. 2, pp. 174–199, 2019.
[23] M. Narasimha and S. Ramesh, “Coating Performance on Carbide Inserts,” International Journal of Engineering and Technical Research, vol. 2, no. 8, pp. 175–179, 2014.
[24] S. M. S. W. Zeng, Conductive Nanoﬁbres and Nanocoatings for Smart Textiles, pp. 92–128, Woodhead Publ Ser Text, Cambridge, UK, 2013.
[25] V. P. Tabakov, A. S. Vereschaka, and A. A. Vereschaka, “Multilayer composition coatings for cutting tools: formation and performance properties,” Mechanics & Industry, vol. 18, no. 7, p. 706, 2017.
[26] S. C. Santos, W. F. Sales, F. J. Da Silva, S. D. Franco, and M. B. Da Silva, “Tribological characterisation of PVD coatings for cutting tools,” Surface and Coatings Technology, vol. 184, no. 2-3, pp. 141–148, 2004.
[27] A. Vereschaka, M. Volosova, A. Chigarev, and N. Sitnikov, “Influence of the thickness of a nanolayer composite coating on values of residual stress and the,” Nature of Coating Wear, vol. 10, p. 63, 2020.
[28] S. Krishna, Handbook of Thin-Film Deposition Processes and Techniques: Principles, Methods, Equipment, and Applications, Noyes Publications, Norwich, N.Y, USA, 2002.
[29] R. Haubner, “The history of hard CVD coatings for tool applications at the University of Technology Vienna,” International Journal of Refractory Metals and Hard Materials, vol. 41, pp. 22–34, 2013.
[30] R. Connelly, A. K. Pattanaik, and V. K. Sarin, “Development of moderate temperature CVD Al2O3 coatings,” International Journal of Refractory Metals and Hard Materials, vol. 23, no. 4-6, pp. 317–321, 2005.
[61] A. Vereschaka, A. Kutin, N. Sitnikov, G. Oganyan, and O. Sharipov, “Research of mechanical and cutting properties, wear and failure mechanisms of nano-structured multilayered composite coating Ti-TiN-(NbZrAl)N,” *Epoxynyag - Journal of Silicate Based and Composite Materials*, vol. 68, no. 4, pp. 114–118, 2016.

[62] A. S. Vereschaka, A. A. Vereschaka, D. V. Sladkov, A. Y. Aksenenko, and N. N. Sitnikov, “Control of structure and properties of nanostructured multilayer composite coatings applied to cutting tools as a way to improve efficiency of technological cutting operations,” *Journal of Nano Research*, vol. 37, pp. 51–57, 2016.

[63] A. Vereschaka, M. Migranov, G. Oganyan, C. S. Sotova, and A. Batako, “Application of carbide cutting tools with nano-structured multilayer composite coatings for turning austenitic steels, type 16Cr-10Ni,” *Mechanics & Industry*, vol. 18, no. 7, p. 707, 2017.

[64] A. S. Vereschaka, A. A. Vereschaka, and M. S. Migranov, “The study wear resistance of the modified surface of the cutting tool,” *Applied Mechanics and Materials*, vol. 548–549, pp. 417–421, 2014.

[65] D. Vereschaka, A. Batako, and V. Adl, “A Development of modifying compounds for multilayer nano-structured coatings for cutting tools,” *Int. J. Nanotechnology*, 14. ISSN, vol. 1475-7435, pp. 574–583, 2017.

[66] B. Y. Vereschaka, A. Aa, M. A. Volosova, D. B. Batako, and A. S. Vereschaka, “Mokritskii, Development of wear-resistant coatings compounds for high-speed steel tool using a combined cathodic vacuum arc deposition,” *International Journal of Advanced Manufacturing Technology*, vol. 84, pp. 1471–1482, 2016.

[67] E. Molland E. Bergmann, “Hard coatings by plasma-assisted PVD technologies: industrial practice,” *Surface and Coatings Technology*, vol. 37, pp. 483–509, 1989.

[68] P. Martin and A. V. Bendavid, “Review of the filtered vacuum arc process and materials deposition,” *Thin Solid Films*, vol. 394, pp. 1–14, 2001.

[69] A. A. V. P. S. N. G. S. Tabakov, “Investigation of wear mechanisms for the rake face of a cutting tool with a multilayer composite nanostructured Cr-CrN-(Ti,Cr,Al,Si) N coating in high-speed steel turning,” *Wear*, vol. 438–439, 2019.

[70] H. Rabat, C. Andreazza, B. Pascal et al., “Carbon/Platinum Nanotextured Films Produced by Plasma Sputtering to Cite This Version: HAL Id: Hal-00338141,” *Engineering Sciences [physics]*, 2009.

[71] V. Alexey, “Improvement of working efficiency of cutting tools by modifying its surface properties by application of wear-resistant complexes,” *Advanced Materials Research*, vol. 712, pp. 347–351, 2013.

[72] I. D. A. S. Vereschaka and O. I. Obreexov, “Development of technology for the synthesis of vacuum arc coating assisting by a high-energy ions,” in *Proceedings of the Int. Scient. Conf. “Protocol”*, Vol. 1. M, p. 139, Sao Paulo, Brazil, July 2002.

[73] C. G. A. Panckow, D. Sladkov, P. K. Singh et al., “Surf., Surf. Coat. Technol.,” in *Proceedings of the 31st International Conference on Metallurgical Coatings and Thin Films*, vol. 214, pp. 188-189, San Diego, CA, USA, April 2004.

[74] S. N. Grigoriev, “Study of cutting properties and wear pattern of carbide tools with comprehensive chemical-thermal treatment and nano-structured/gradient wear-resistant coatings,” *Mécanique & Industries*, vol. 17, no. 7, 2016.

[75] S. Odake, H. Ohfuji, T. Okuchi, H. Kagri, H. Sumiya, and T. Irifune, “Pulsed laser processing of nano-polycrystalline diamond: a comparative study with single crystal diamond,” *Diamond and Related Materials*, vol. 18, no. 5–8, pp. 877–880, 2009.

[76] M. A. Volosova, Y. A. Melnik, A. A. Vereschaka, and D. N. Lytkin, “Research of the cutting of materials used in heavy power engineering by means of the carbide cutting tools with nanoscale wear-resistant coating,” *Mécanique & Industries*, vol. 17, no. 7, 2016.

[77] H. A. Bahr, H. Balke, T. Fett et al., “Cracks in functionally graded materials,” *Materials Science and Engineering A*, vol. 362, no. 1-2, pp. 2-16, 2003.

[78] D. Berend, D. Marc-André, L. Yanwei, and T. Mirko, “Automatic regeneration of cemented carbide tools for a resource efficient tool production,” *Procedia Manufacturing*, vol. 21, pp. 259–265, 2018.

[79] K. Vasilko and Z. Murčinková, “Tool life extension methods for cut-off tools made of high-speed steel,” *Procedia Engineering*, vol. 149, pp. 520–525, 2016.

[80] S. N. Grigoriev, S. V. Fedorov, and K. Hamdy, “Materials, properties, manufacturing methods and cutting performance of innovative ceramic cutting tools À a review,” *Manufacturing Review*, vol. 19, 2019.

[81] S. Stekovic, “Low Cycle Fatigue and Thermo-Mechanical Fatigue of Uncoated and Coated Nickel-Base Superalloys,” 2017, https://www.diva-portal.org/smash/get/diva2:24183/FULLTEXT01.pdf.

[82] J. A. Ghani, G. A. Ibrahim, and H. C. H. Che, “Tool wear mechanism in continuous cutting of difficult-to-cut material under dry machining,” *Advanced Materials Research*, vol. 126–128, pp. 195–201, 2010.

[83] J. Xu, C. Li, M. E. Mansori, G. Liu, and M. Chen, “Study on the frictional heat at tool-work interface when drilling CFRP composites,” *Procedia Manufacturing*, vol. 26, pp. 415–423, 2018.

[84] S. Lampman, M. Schneider, and M. S. Chatterjee, “Introduction to surface hardening of steels,” *ASM Handbook, Steal Heat Treating Fundam.*. *Process*, vol. 4, pp. 389–398, 2013.

[85] S. P. D. S. Deevi, “Single layer and multilayer wear resistant coatings of (Ti,Al)N: a review,” *Materials Science and Engineering*, vol. 3, pp. 58–79, 2003.

[86] N. A. M. Aliofkhazraei, “Nano- and Microscale Processing – Modeling,” *Compr. Mater. Process, Elsevier, Amsterdam, Netherlands, 2014.*

[87] A. W. Wright, “Production of transparent metallic film,” *American Journal of Science*, vol. s3-13, no. 73, pp. 49–55, 1877.

[88] R. Haubner, E. Rauchenwald, M. Lessiak, R. Pitonak, and R. Weissenberg, “Novel high-performance CVD coatings for machining applications,” *Powder Metallurgy Progress*, vol. 18, no. 2, pp. 128–138, 2018.

[89] A. Bendavid and P. J. Martin, “Review of thin film materials deposition by the filtered cathodic vacuum arc process at CSIRO,” *Journal of the Australian Ceramic Society*, vol. 50, pp. 86–101, 2014.

[90] W. I. Milne, B. S. Satynarayana, A. Hart, and J. Robertson, “Electron emission from amorphous and nanocluster carbon films grown by the cathodic arc process,” *Applied Surface Science*, vol. 159-160, pp. 561–566, 2000.

[91] D. M. Sanders and A. Anders, “Review of cathodic arc deposition technology at the start of the new millennium,” *Surface and Coatings Technology*, vol. 78, pp. 133–190, 2000.

[92] J. R. Creighton and P. Ho, “Chapter 1 introduction to chemical vapor deposition (CVD),” *Chemical Vapor Deposition*, pp. 1–13, Springer, Mannheim, NY, USA, 2001.
[93] J. Park, "Chemical vapour deposition of polymers: principles, materials and applications," *Chem. Vap. Depos. Surf. Eng. Ser.* vol. 2, pp. 243–246, 2001.

[94] K. Czechowski, I. Pofelska-Filip, B. Królicka, and P. Szlosek, "Effect of nitride nano-scale multilayer coatings on functional properties of composite ceramic cutting inserts," *Bulletin of the Polish Academy of Sciences, Technical Sciences*, vol. 53, no. 4, pp. 425–431, 2005.

[95] J. Vetter, T. Krug, and V. V. D. Heide, "ALTiCrNO Coatings for Dry Cutting Deposited by Reactive Cathodic Vacuum Arc Evaporation," *Surface and Coatings Technology*, vol. 174, 2003.

[96] M. Alexander, S. Grigoriev, M. Yury, P. Vitaly, and P. Vladimir, "Cutting tools nitriding in plasma produced by a fast neutral molecule beam," *Journal of Applied Physics*, vol. 50, no. 8, Article ID 08JG04, 2011.

[97] V. A. Dodonov and I. A. Silaev, "Operating properties of ultrafine-grained coatings," *ITO*, vol. 1, pp. 23–27, 2000.

[98] I. I. Aksenov and V. M. Khoroshikh, *Streams of Particles, Their Mass Transfer in Vacuum Arc*, p. 1984, CNIIatominform, Moscow, Russia, 1984.

[99] K. Akari, T. Kumakiri, K. Tsuji, E. S. Koh, and C. N. Tai, "Reduction In Macroparticles During The Deposition Of Tin Films Prepared By Arc Ion Plating," *Metallurgical Coatings and Thin Films 1990*, vol. 43–44, pp. 312–323, 1990.

[100] R. L. Boxman and S. Goldsmith, "Principles and applications of vacuum arc coatings," *IEEE Transactions on Plasma Science*, vol. 17, no. 5, pp. 705–712, 1989.