Analysis of the Influence of Tool Coating Materials on Cutting Efficiency and Surface Quality

Duo Zhang, Haoqiang Zhang, Suoxia Hou, Xinge Wang

College of Mechanical Engineering, North China University of Science and Technology, Tangshan, China

Abstract

This paper presents an in-depth analysis of the impact of tool coating materials on cutting efficiency and surface quality in machining operations. The study begins with an overview of the various types of tool coating materials, including titanium nitride (TiN), titanium carbonitride (TiCN), aluminum oxide (Al2O3), zirconium nitride (ZrN), and diamond-like carbon (DLC). Each coating material is characterized by unique properties such as hardness, thermal stability, and chemical resistance, which are crucial for their performance in specific machining applications. The importance of cutting efficiency is emphasized, highlighting its direct correlation with manufacturing productivity and cost. Cutting efficiency is influenced by a multitude of factors, including cutting speed, feed rate, depth of cut, tool geometry, workpiece material, use of cutting fluids, and machine tool rigidity. The interplay between these factors and the role of tool coatings in optimizing them is explored. It is evident that coatings can significantly reduce tool wear, lower friction, and improve thermal stability, leading to more efficient machining processes. The paper also discusses the impact of tool coatings on surface quality, a critical factor in determining the final product's aesthetic and functional attributes. Coatings can enhance surface finish by reducing the tool-chip contact, minimizing vibrations, and controlling chip formation. The study underscores the need for selecting the appropriate coating material based on the machining operation's specific requirements. In conclusion, the research underscores the significance of tool coatings in achieving high cutting efficiency and superior surface quality. The findings suggest that a strategic selection of tool coatings can lead to reduced production costs, improved product quality, and enhanced competitiveness in the manufacturing sector. The paper calls for further research to explore emerging coating technologies and their potential to revolutionize machining processes.

Keywords

Tool Coatings; Cutting Efficiency; Surface Quality; Machining Processes.

1. Introduction

1.1 Background

The manufacturing industry is continually evolving, with a strong emphasis on improving the efficiency and quality of production processes. Cutting tools are integral to these processes, playing a pivotal role in shaping the final product. As technology advances, so too does the range of materials available for enhancing the performance of these tools. One such enhancement is the application of tool coatings, which have become a standard practice in modern machining operations. These coatings are designed to reduce friction, increase tool life, and improve the surface finish of machined parts. The development of tool coatings can be traced back to the early 20th century with the

ISSN: 2414-1895 DOI: 10.6919/ICJE.202411_10(11).0012

introduction of titanium nitride (TiN), which was a significant breakthrough at the time. Since then, a variety of coatings, including titanium carbide (TiC), aluminum oxide (Al_2O_3), and diamond-like carbon (DLC), have been introduced to cater to the diverse needs of different machining applications. The choice of coating material is crucial as it can significantly affect the performance of the cutting tool. For instance, a coating with high hardness can resist wear, while a coating with low friction coefficient can reduce heat generation and improve the tool's lifespan. [1]Additionally, the thermal conductivity, and adhesion to the substrate are also critical factors that determine the coating's suitability for a particular application. As machining processes become more complex and the demand for higher precision components increases, the role of tool coatings in achieving these goals becomes even more critical. The background of this study is set against the backdrop of this technological evolution. It seeks to delve into the world of tool coatings, examining their properties, and how they influence the efficiency and quality of cutting operations. This exploration is essential as it can provide manufacturers with the knowledge needed to select the most appropriate coatings for their tools, thereby optimizing their production processes, like this picture.[2].

Figure 1. Coated Cutting Tools

1.2 Significance of the Study

The significance of this study is rooted in the current industrial landscape, where competition is fierce, and the demand for high-quality products is ever-increasing. Manufacturers are constantly seeking ways to improve their processes to reduce costs, increase productivity, and enhance the quality of their products. Tool coatings offer a tangible means to achieve these goals, and understanding their impact is crucial. This study is significant for several reasons. Firstly, it provides a comprehensive analysis of the various types of tool coatings available and their properties. This analysis is essential for manufacturers who need to make informed decisions when selecting coatings for their cutting tools. Secondly, the study examines the impact of these coatings on cutting efficiency, which is a critical factor in the overall productivity of machining operations. By understanding how different coatings affect efficiency, manufacturers can optimize their processes to achieve higher throughput with less waste.[3]Thirdly, the study assesses the influence of tool coatings on surface quality, which is a key determinant of product quality. In industries such as aerospace and automotive, where precision and finish are paramount, the choice of coating can make the difference between a successful product and a failure. Lastly, this research aims to provide recommendations for the selection of tool coatings based on specific machining requirements, which can guide manufacturers in making more strategic choices, like this picture.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202411_10(11).0012

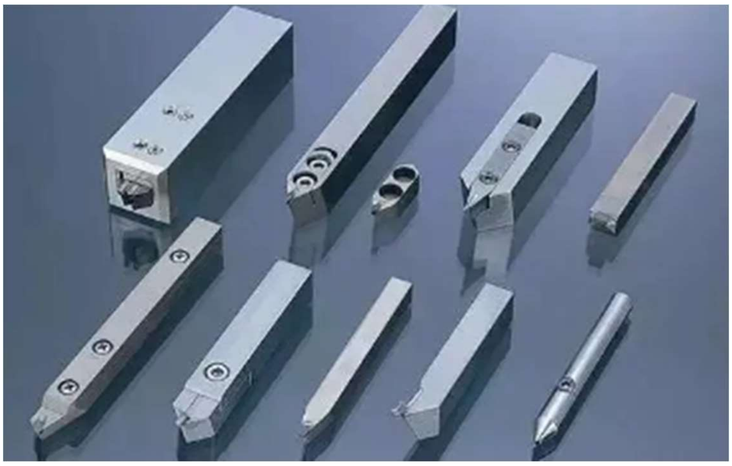

Figure 2. Diamond coated cutting tool

1.3 Objectives of the Study

The objectives of this study are designed to provide a thorough understanding of the role of tool coatings in machining operations. The primary objectives are as follows: To conduct a detailed investigation into the various types of tool coating materials available in the market, including their chemical composition, physical properties, and mechanisms of action.[4]

To analyze the impact of these coatings on the cutting efficiency of tools during different machining operations, such as turning, milling, and drilling. This will involve examining how coatings affect factors like tool life, cutting speed, and power consumption.

To assess the influence of tool coatings on the surface quality of machined components, including aspects like surface roughness, dimensional accuracy, and the presence of defects.

To provide practical recommendations for the selection of tool coatings based on the specific requirements of different machining processes. This will involve considering factors such as the material being machined, the desired surface finish, and the operational conditions.

To offer insights into potential areas for future research in the field of tool coatings, identifying gaps in current knowledge and suggesting directions for further exploration.

By achieving these objectives, this study aims to contribute to the body of knowledge surrounding tool coatings and their applications in machining. The findings will be valuable not only to tool manufacturers but also to end-users in the manufacturing industry, helping them to optimize their processes and improve the quality of their products, like this table.[5].

Table 1. Comparison of Tool Coating Materials

Coating Material	Hardness	Thermal Stability
Titanium Nitride (TiN)	High	Moderate
Titanium Carbonitride (TiCN)	Very High	High

2. Tool Coating Materials

2.1 Types of Coating Materials

Tool coating materials have evolved significantly over the years, and today, a variety of coatings are available to cater to different machining requirements. The primary types of tool coating materials can be categorized based on their chemical composition and physical properties. Some of the most common types include:

Titanium Nitride (TiN): Known for its golden color, TiN is one of the earliest and most widely used coatings. It offers a good balance of hardness, wear resistance, and thermal stability.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202411_10(11).0012

Titanium Carbonitride (TiCN): This coating is an improvement over TiN, with enhanced hardness and wear resistance. It is particularly effective in high-speed machining applications.

Aluminum Oxide (Al2O3): Al2O3 provides excellent oxidation resistance and is often used for its ability to withstand high temperatures without losing its hardness.

Zirconium Nitride (ZrN): ZrN is known for its low friction coefficient, which makes it suitable for applications where reduced tool-chip contact is desired.

Diamond-Like Carbon (DLC): DLC coatings are amorphous and exhibit properties similar to diamond, such as extreme hardness and low friction. They are often used for their anti-wear and anti-galling properties.[6]

Physical Vapor Deposition (PVD) Coatings: PVD coatings like Titanium Aluminum Nitride (TiAlN) offer a combination of high hardness, thermal stability, and oxidation resistance, making them suitable for a wide range of applications.

Chemical Vapor Deposition (CVD) Coatings: CVD coatings, such as those containing diamond or cubic boron nitride (CBN), are known for their exceptional hardness and thermal conductivity, which is beneficial for high-temperature machining.

Each of these coatings has its unique set of advantages and is chosen based on the specific requirements of the machining process, including the type of material being machined, the desired surface finish, and the operational conditions, like this table.

Table 2. Impact of Tool Coating Materials on Machining Parameters

Coating Material	Tool Life Extension	Cutting Speed Increase
Titanium Nitride (TiN)	Moderate	Moderate
Titanium Carbonitride (TiCN)	High	High

2.2 Properties of Coating Materials

The properties of tool coating materials are critical to their performance in machining operations. Some of the key properties that influence the choice of coating include:

Hardness: A hard coating can resist wear and prolong the life of the cutting tool.

Thermal Stability: Coatings with high thermal stability can maintain their properties at elevated temperatures, which is essential for high-speed machining.[7]

Oxidation Resistance: Coatings that resist oxidation are less likely to degrade at high temperatures, ensuring consistent performance.

Friction Coefficient: A low friction coefficient can reduce heat generation and tool wear, leading to better surface finish and extended tool life.

Adhesion: Good adhesion to the substrate ensures that the coating does not peel off during machining, maintaining its protective function.

Chemical Stability: Coatings that are chemically stable are less likely to react with the workpiece material, which can be important in maintaining the integrity of the workpiece and the tool.

Thermal Conductivity: Coatings with high thermal conductivity can dissipate heat more effectively, reducing the risk of thermal damage to the tool or workpiece.

Transparency to Lubricants: Some coatings are designed to allow cutting fluid to penetrate to the tool-chip interface, which can improve lubrication and reduce friction.

These properties are not mutually exclusive, and coatings are often engineered to have a combination of these properties to meet the specific demands of the machining process.

2.3 Application of Coating Materials in Cutting Tools

The application of coating materials in cutting tools is a critical step in the manufacturing process. The choice of coating can significantly affect the performance of the tool in various ways:

Tool Life: Coatings can extend the life of cutting tools by reducing wear and protecting the tool from the high temperatures generated during machining.

Cutting Speeds: Certain coatings, such as those with high thermal stability, allow for higher cutting speeds without compromising tool performance.

Surface Finish: Coatings with low friction coefficients can lead to improved surface finish on the workpiece, reducing the need for post-machining finishing processes.

Chip Control: Coatings can influence the formation and breakage of chips, which can affect the overall efficiency of the machining process.[8]

Reduced Vibration: Some coatings can reduce tool vibration, leading to more stable machining operations and improved part accuracy.

Cost Savings: By reducing tool wear and the need for frequent tool changes, coatings can lead to cost savings in the long run.

Environmental Considerations: Coatings can reduce the need for cutting fluids, which can have a positive impact on the environment by reducing the use of potentially harmful substances.

Specialized Applications: Certain coatings are designed for specific applications, such as machining hard materials or working in corrosive environments.

The application of these coatings is a carefully considered decision that takes into account the type of machining operation, the workpiece material, and the desired outcomes. By understanding the properties of the coatings and how they apply to specific cutting tools, manufacturers can optimize their machining processes for improved efficiency and quality.

3. Cutting Efficiency

3.1 Definition and Importance

Cutting efficiency in machining operations refers to the ability to remove material from a workpiece at a high rate while maintaining the desired level of precision and surface finish. It is a critical parameter that directly impacts the productivity and cost-effectiveness of manufacturing processes. High cutting efficiency can lead to reduced cycle times, lower energy consumption, and increased throughput, all of which contribute to a more competitive manufacturing environment. The importance of cutting efficiency cannot be overstated. In an industry where time is money, the ability to machine parts quickly without sacrificing quality is essential. It allows manufacturers to meet tight production schedules and deliver products to market faster. Additionally, efficient cutting processes can reduce waste and minimize the consumption of raw materials, which is not only cost-effective but also aligns with sustainable manufacturing practices.[9]

3.2 Factors Affecting Cutting Efficiency

Several factors can influence the cutting efficiency of a machining operation, including: Cutting Speed: The rate at which the cutting tool moves through the workpiece can significantly affect efficiency. Higher speeds can lead to faster material removal rates but must be balanced against the potential for increased tool wear and heat generation. Feed Rate: The feed rate, or the distance the tool moves perpendicular to the cutting edge per revolution, also plays a crucial role. An optimal feed rate ensures efficient material removal without causing excessive tool wear or leading to poor surface finish. Depth of Cut: The depth of cut affects the amount of material removed per pass. A deeper cut can lead to higher efficiency but may also result in increased cutting forces and the potential for tool breakage if not managed properly.[10]Tool Geometry: The shape and angle of the cutting tool can influence the cutting efficiency. Proper tool geometry ensures that the cutting edges are sharp and can remove material effectively without causing excessive heat or vibration. Workpiece Material: The hardness, toughness, and thermal conductivity of the workpiece material can affect how easily it can be machined. Some materials are more challenging to cut than others, requiring adjustments to cutting parameters for optimal efficiency. Cutting Fluids: The use of cutting fluids can improve lubrication and cooling, reducing friction and heat, which can enhance cutting efficiency. Machine Tool Rigidity: The rigidity of the machine tool can affect the stability of the cutting process, with a more rigid setup allowing for higher cutting speeds and feeds without causing vibrations or tool deflection.[11]

3.3 Impact of Tool Coating Materials on Cutting Efficiency

The choice of tool coating material can have a profound impact on cutting efficiency. Coatings can enhance the performance of cutting tools in several ways: Reduced Friction: Coatings with low friction coefficients can reduce the resistance between the tool and the workpiece, leading to less heat generation and less energy required to remove material. Increased Tool Life: Coatings can protect the cutting tool from wear, extending its life and reducing the need for frequent tool changes, which can disrupt the machining process and affect efficiency. Improved Thermal Stability: Coatings with high thermal stability can maintain their properties at elevated temperatures, allowing for higher cutting speeds without the risk of tool failure. Enhanced Surface Finish: Some coatings can lead to a smoother surface finish on the workpiece, reducing the need for additional finishing operations and contributing to higher efficiency. Resistance to Adhesive Wear: Coatings can reduce the tendency for workpiece material to adhere to the tool surface, which can cause built-up edge and reduce cutting efficiency. Chemical Stability: Coatings that are chemically stable can resist reactions with the workpiece material, maintaining the integrity of both the tool and the workpiece and ensuring consistent cutting performance. In conclusion, the selection of the appropriate tool coating material is crucial for achieving high cutting efficiency. By understanding how different coatings can affect the performance of cutting tools, manufacturers can optimize their machining processes to achieve greater productivity and cost savings.

4. Conclusion

In conclusion, the research has demonstrated that tool coating materials significantly influence the cutting efficiency and surface quality in machining operations. The study has shown that coatings can reduce tool wear, lower friction, and improve thermal stability, all of which contribute to more efficient machining processes. The findings also indicate that the right choice of coating material can lead to better surface finishes and dimensional accuracy, which are critical for high-quality manufacturing. It is evident that the application of tool coatings is not just a matter of enhancing tool performance but also a strategic decision that can impact the overall productivity and competitiveness of a manufacturing operation. Future research should continue to explore advancements in coating technologies and their applications to further optimize machining processes and meet the evolving demands of the manufacturing industry.

References

[1] Zanoelo, Maiara,BarbosaDekker, Aneli M.,Dekker, Robert F. H., et al.Microencapsulation of roasted mate tea extractives with lasiodiplodan (a (1 →6)- β-D-glucan) and maltodextrin as combined coating materials: A strategic tool to stabilize and protect the bioactive components[J].INTERNATIONAL JOURNAL OF BIOLOGICAL MACROMOLECULES,2024,275.DOI:10.1016/j.ijbiomac.2024.133615.

[2] Moravcikova, Jana,Moravcik, Roman,Sahul, Martin, et al.Influence of Laser Texturing and Coating on the Tribological Properties of the Tool Steels Properties[J].MACHINES,2024,12(05). DOI:10.3390/machines12050311.

[3] Akbar, Faraz,Arsalan, Muhammad.Experimental investigation of uncoated, single layer, and multilayer-coated TiAlN/TiN tool inserts in dry orthogonal cutting of AISI/SAE 4140 alloy steel[J].PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART B-JOURNAL OF ENGINEERING MANUFACTURE,2024,238(1-2):95-107.DOI:10.1177/09544054231157247.

[4] Zhang, Jingjie,Zhang, Guoqing,Fan, Guanghui.Effects of tool coating materials and coating thickness on cutting temperature distribution with coated tools[J].INTERNATIONAL JOURNAL OF APPLIED CERAMIC TECHNOLOGY,2022,19(04):2276-2284.DOI:10.1111/ijac.14038.

[5] Das, Anshuman,Kumar, Anuj,Padhan, Smita, et al.Hard turning of AISI H10 steel using AlTiN and AlTiSiN coated carbide tools: comparative machining performance evaluation and economic assessment[J].JOURNAL OF THE BRAZILIAN SOCIETY OF MECHANICAL SCIENCES AND ENGINEERING,2024,46(05).DOI:10.1007/s40430-024-04855-5.

[6] Nanshie, Vanella Mbakop,Aidibe, Ali,Heidari, Majid, et al.Impact of coating and microstructure on wear resistance of tool steels for wood cutting: a novel approach to quantification and analysis of wear-related damages[J].JOURNAL OF WOOD SCIENCE,2024,70(01).DOI:10.1186/s10086-024-02132-6.

[7] Petersen, Hilke,Dias, Nelson Filipe Lopes,Breidenstein, Bernd, et al.Old Tool Materials in a New Dress[J].ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb,2024,119(7-8):548-552.DOI:10.1515/zwf-2024-1091.

[8] da Costa, Danusa Silva,dos Santos, Lucely Nogueira,Takeuchi, Katiuchia Pereira, et al.Properties of films and coatings added of tocopherol for food packaging: tool-based review for systematic reviews and bibliometric analysis[J].BRITISH FOOD JOURNAL,2024,126(13):226-268.DOI:10.1108/BFJ-04-2023-0292.

[9] Nogueira, Francisca R.,Pedroso, Andre F. V.,Silva, Francisco J. G., et al.A Comparative Study on the Wear Mechanisms of Uncoated and TiAlTaN-Coated Tools Used in Machining AMPCO® Alloy[J].COATINGS,2024,14(01).DOI:10.3390/coatings14010004.

[10] Bhat, Hina F.,Amin, Nuzhat,Nasir, Zarka, et al.Keratin as an effective coating material for in vitro stem cell culture, induced differentiation and wound healing assays[J].HELIYON,2024,10(05). DOI:10.1016/j.heliyon.2024.e27197.

[11] Venkatesh, R.,Anbumalar, V,Rajakarunakaran, S., et al.Optimizing machining efficiency: a comprehensive study on PVD cathodic arc evaporation coated turning tool inserts with TiAlN/AlCrN multilayer coatings[J].MATERIALS RESEARCH EXPRESS,2024,11(06).DOI:10.1088/2053-1591/ad507e.