

Nanodiamond Composite Films Deposited by Coaxial Arc Plasma Deposition on Cemented Carbide for Advanced Cutting Tools Applications

モハメド ラガブ ディアブ

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氏 名 Name : Mohamed Ragab Diab
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れたナノダイヤモンド複合膜の先進切削工具応用)
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ABSTRACT

Cemented carbide (WC-Co) is a pivotal material utilized in high-performance cutting tools; however, its durability can be significantly enhanced through the application of hard coatings. Nanodiamond composite (NDC) films, comprising nanodiamond crystals embedded within an a-C matrix, demonstrate exceptional hardness, low friction, and high wear resistance, rendering them a promising solution for the enhancement of tool performance. This dissertation presents a comprehensive investigation into the development of durable and adherent NDC coatings on WC-Co substrates via the coaxial arc plasma deposition (CAPD) technique. This research systematically assesses the influence of various deposition parameters on the properties of the NDC films, while also addressing the significant adhesion challenges linked to the cobalt binder.

The findings underscore the importance of the target-substrate distance (TSD) during the deposition process. An optimal TSD of 10 mm was established, which resulted in films exhibiting a hardness of 49.12 GPa and a Young's modulus of 420 GPa. Furthermore, the application of a negative bias voltage during deposition markedly improved the mechanical properties of the films. Biased films achieved hardness levels reaching up to 82 GPa and Young's modulus of 780 GPa, attributed to increased ion energy and enhanced film densification resulting from their nanocomposite structure. However, the implementation of higher bias voltages correspondingly raised internal compressive stress from 1.28 GPa to 4.53 GPa, which adversely impacted adhesion and diminished the critical load for delamination from 14 N to 9 N.

In an effort to mitigate cobalt-induced graphitization and to manage high internal stress, Si-doping was incorporated into the NDC films. This strategy facilitated the formation of robust C-C sp^3 and C-Si sp^3 bonds while effectively reducing the occurrence of weaker C=C sp^2 bonds. When combined with optimized negative bias voltages, this approach successfully modulated stress levels and improved mechanical stability. Additionally, the introduction of a strategically placed Al interlayer was investigated. A 100 nm Al interlayer resulted in a remarkable 79% increase in adhesion strength by creating a dense Al_2O_3 interfacial barrier that alleviated cobalt-induced graphitization and stress. This configuration also achieved a 62% enhancement in wear resistance, while concurrently reducing the coefficient of friction (COF) to ≤ 0.09 .

A comparative analysis with conventional hot filament chemical vapor deposition (CVD) diamond coatings highlighted the advantages of the CAPD-deposited NDC films. The CAPD process facilitated rapid deposition rates (3.5 $\mu\text{m/h}$) on unheated WC-Co substrates, providing an environmentally friendly alternative that does not necessitate the use of reactive gases or chemical pre-treatment. The resulting coatings exhibited superior adhesion characteristics while sustaining a low and stable COF throughout extended dry sliding tests. The exceptional hardness (up to 82 GPa) and fracture resistance ($H^3/E^2 = 0.9$ GPa) of the NDC coatings can be attributed to their self-lubricating nanocomposite architecture, ensuring remarkable durability under abrasive wear conditions.

In conclusion, this research substantiates the feasibility of producing high-performance NDC coatings through the CAPD method. By strategically regulating deposition parameters, incorporating Si doping, and engineering interlayers, this study establishes a robust and sustainable framework for the development of advanced protective coatings specifically designed for extreme machining environments.