

**ADVANCED ION-PLASMA SURFACE ENGINEERING OF HIGH-SPEED STEEL
CUTTING TOOLS FOR MACHINING DIFFICULT-TO-CUT ALLOYS**

Jamshid Sharipov

Asia International University, Bukhara, Uzbekistan

E-mail: jamshid_sharipov_85@mail.ru

Correspondence: jamshid_sharipov_85@mail.ru

Abstract. High-speed steel cutting tools are still widely used in machining operations involving complex geometries and high dynamic loads. However, their application is limited by intensive wear and plastic deformation at elevated temperatures. This study investigates a complex ion-plasma surface modification approach combining ion nitriding, ion alloying, and multilayer nitride-based coatings to improve the wear resistance and operational stability of high-speed steel tools. Ion nitriding was applied to form a hardened diffusion layer, followed by ion alloying using Nb-Hf systems and the deposition of a (TiAl)N-based coating. Cutting tests performed during machining of a chromium-nickel alloy demonstrated a significant reduction in cutting forces and a 3–4-fold increase in tool life compared to conventionally coated tools.

Keywords: high-speed steel; ion nitriding; ion alloying; multilayer coatings; wear resistance; cutting tools

1. Introduction

High-speed steels (HSS) remain an important class of materials for cutting tools due to their high toughness, bending strength, and resistance to brittle fracture. Despite the rapid development of carbide and ceramic tools, HSS tools are indispensable in machining operations involving intermittent cutting and complex tool geometries. The main limitation of HSS tools is their insufficient resistance to wear and plastic deformation under severe cutting conditions. Recent studies indicate that the performance of wear-resistant coatings strongly depends on the mechanical stability and physicochemical state of the subsurface layer.

Disk milling cutters manufactured from R6M5 high-speed steel were used as the substrate material. Surface modification was carried out in three sequential stages: ion nitriding, ion alloying, and coating deposition. Ion nitriding was performed at a temperature of 470 °C to form a nitrogen-enriched diffusion layer. Ion alloying was conducted using Nb-Hf alloy targets activated by a low-energy high-current electron beam. Finally, a multilayer (TiAl)N-based coating was deposited using physical vapor deposition technology.

Microstructural analysis confirmed the formation of a multilayer surface system consisting of a hardened diffusion layer, an alloyed transition zone, and a nanostructured wear-resistant coating. X-ray diffraction analysis revealed the presence of stable nitride phases with high thermal stability. Cutting experiments showed a reduction in cutting forces and power consumption when using complex-treated tools. The suppression of plastic deformation in the cutting edge was identified as the dominant mechanism responsible for the observed increase in tool life. In recent years, the range of carbide end mills produced by the tool industry has been so broad that enterprises now have an alternative tool selection to solve any technological problem fig.1. A variety of end mills with a spherical cutting part has a conical barrel-shaped geometry that smoothly turns into a spherical end. It is an advanced and promising tool for finishing curved surfaces, which, like the classic ball end mills, should not be deprived of the attention of specialists. Production experience shows that the milling efficiency of precision products made of heat-resistant nickel alloy primarily depends on the cutting ability of the tool. Therefore, the task of ensuring maximum wear resistance of end mills emerges

into prominence [5] in combination with an acceptable performance by applying a high cutting speed and reducing the time of auxiliary operations (for tool change). It should be noted that the preservation of a longer time period of cutting ability of ball-shaped end mills aims to solve another technological problem, this being ensuring the possibility of part typical surfaces machining in one setup without the retraction and new plunge-in of the tool. Changing the cutter directly during machining often leads to an error in the shape and size of the part and the appearance of gouges and other unacceptable defects for the aircraft industry [6-7].

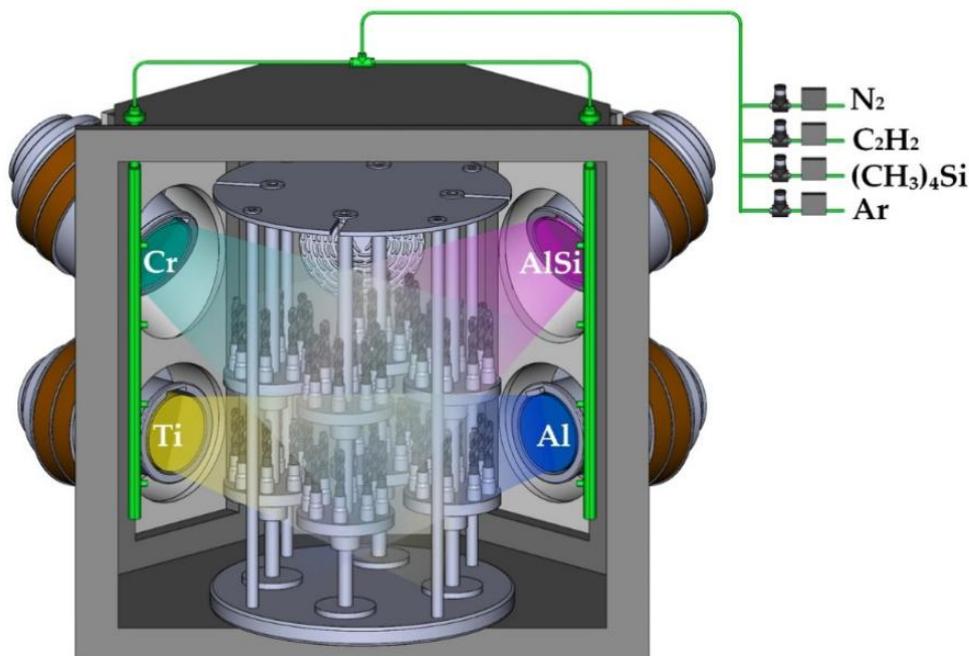


Figure 1. Schematic diagram of a hybrid vacuum-plasma installation for vacuum arc and gas-phase coatings' deposition.

Considering that high-temperature nickel alloys have low thermal conductivity and a high tendency to adhere to cemented carbide, the state of the cutting edge (with rake and flank faces forming it) will determine the end mill's cutting ability. The temperature near the cutting edge determines the tool wear intensity in milling Inconel alloys to a greater extent. However, despite the existing possibilities of using more heat-resistant oxide and nitride tool ceramics, cemented carbide will remain the primary tool material in the long term due to less brittleness. For example, Fernandez-Lucio, P. et al. [8], after testing cemented carbide (uncoated and coated with AlTiN, the thickness of the coating was not provided) and SiAlON ceramics in milling Inconel(R) until the end of their useful life (criterion was tool wear reaching 0.3 mm or a fatal failure), stated that coated carbide is not ultimately suitable for milling at higher speeds, unlike tool ceramics. The application of wear-resistant coatings based on nitrides and oxides of refractory metals aims to increase the microhardness of the tool contact pads, ensuring their physicochemical passivity (reducing the coefficient of friction) concerning the material to be machined, a combination of which should increase the end mill's cutting ability [9].

It is known from classical works in the field of the theory of cutting materials that the power of heat-generating sources in shaping largely depends on the friction forces on the rake- and flank-working faces of the tool and the work of forces on the contact pads that cause wear. Therefore, their effectiveness in solving the problem of increasing the tool's cutting ability in cutting nickel alloys [10] will, in many respects, depend on the ability of coatings to reduce frictional interaction on the contact pads (while maintaining heat resistance). The aim of this work was to study the ability of DLC

coatings based on a-C:H:Si with a CrAlSiN nitride sublayer to withstand thermal loads in a wide temperature range (varied by choosing a different speed milling mode such as 150, 200, and 250 m/min). The efficiency of DLC coating deposited to cemented carbide ball end mills was evaluated compared to uncoated ball end mills and the samples coated with the well-proven multi-layer gradient TiN–AlN–TiAlN coating under high-temperature conditions (at 20, ~550, ~650, ~850 °C). During the experiments, the particular focus was on assessing the temperature in the cutting zone as the most important and, in many ways, informative parameter. The thermo-EMF (electromotive force) was recorded, which was converted into temperature values according to the corresponding calibration charts using the method of natural thermocouple in the cutting zone. For the first time, the authors compared the behavior of CrAlSiN–DLC and TiN–AlN–TiAlN coatings deposited to ball end mills under operating conditions at different cutting temperatures, with the results of high-temperature tribological tests received on a friction machine. The new experimental results on the assessment of the cutting ability of cemented carbide ball end mills with CrAlSiN–DLC coatings at different levels of thermal loads as well as establishing the effect of coatings on the state of the machined surface of a nickel alloy part can be a step towards expanding the areas of technological application of DLC coatings and their implementation based on new technical solutions for the needs of the aviation industry. The method of vacuum arc deposition was used for the deposition of a two-component nitride coating TiN–AlN–TiAlN and a three-component sublayer CrAlSiN, in which the metal component of the plasma is formed upon evaporation of the cathode material from the cathode spots of the arc discharge, and the reactive gas is supplied to the working zone in an ionized state. A plasma-chemical, gas-phase deposition of carbon condensate was used for the DLC coating's deposition through a chemical reaction and the decomposition of the gas mixture components (the original technology, patented by Platit, Selzach, Switzerland, was taken as a basis).

4. Conclusions

The results demonstrate that complex ion–plasma surface modification is an effective method for improving the performance of high-speed steel cutting tools. Ion nitriding and ion alloying significantly enhance the load-bearing capacity of the substrate and ensure strong adhesion of the coating. The proposed approach provides a 3–4-fold increase in tool life when machining difficult-to-cut alloys and is suitable for industrial application.

References

1. Kumar, A.; Ensha, S.; Irvin, J.F.; Quinn, J. Liquid Metal Corrosion Fatigue (LMCF) Failure of Aircraft Engine Turbine Blades. *J. Fail. Anal. Prev.* **2018**, *18*, 939–947. [CrossRef]
2. McClung, R.C.; Bhamidipati, V. An investigation of small-crack effects in various aircraft engine rotor materials. *Mater. High Temp.* **2016**, *33*, 452–464. [CrossRef]
3. Sahoo, B.; Panigrahi, S.K.; Satpathy, R.K. Creep Life Degradation and Microstructure Degeneration in a Low-Pressure Turbine Blade of a Military Aircraft Engine. *J. Fail. Anal. Prev.* **2017**, *17*, 529–538. [CrossRef]
4. Volkov, A.M.; Karyagin, D.A.; Letnikov, M.N.; Bakradze, M.M.; Perevozov, A.S. Specifics of Producing Disk Blanks for Gas-Turbine Engines Using Granules of Super Heat-Resistant Nickel Alloys. *Metallurgist* **2020**, *64*, 362–369. [CrossRef]
5. Martínez, S.; Ortega, N.; Celentano, D.; Sánchez Egea, A.J.; Ukar, E.; Lamikiz, A. Analysis of the part distortions for Inconel 718 SLM: A case study on the NIST test artifact. *Materials* **2020**, *13*, 5087. [CrossRef] [PubMed]

6. Lee, W.-S.; Lin, C.-F.; Chen, T.-H.; Chen, H.-W. Dynamic Impact Response of Inconel 718 Alloy under Low and High Temperatures. *Mater. Trans.* **2011**, *52*, 1734–1740. [CrossRef]
7. Grzesik, W.; Nieslony, P.; Laskowski, P. Determination of Material Constitutive Laws for Inconel 718 Superalloy Under Different Strain Rates and Working Temperatures. *J. Mater. Eng. Perform.* **2017**, *26*, 5705–5714. [CrossRef]
8. Vereschaka, A.A.; Grigoriev, S.N.; Vereschaka, A.S.; Popov, A.Y.; Batako, A.D. Nano-scale multilayered composite coatings for cutting tools operating under heavy cutting conditions. *Procedia CIRP* **2014**, *14*, 239–244. [CrossRef]
9. Grigoriev, S.N.; Gurin, V.D.; Volosova, M.A.; Cherkasova, N.Y. Development of residual cutting tool life prediction algorithm by processing on CNC machine tool. *Materwiss. Werksttech.* **2013**, *44*, 790–796. [CrossRef]
10. Moufki, A.; Le Coz, G.; Dudzinski, D. End-milling of Inconel 718 Superalloy—An Analytical Modelling. *Procedia CIRP* **2017**, *58*, 358–363. [CrossRef]