Coating-thickness-dependent physical properties and cutting temperature for cutting Inconel 718 with TiAlN coated tools

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Abstract

Introduction: Coating-thickness-dependent physical properties can induce different cutting temperatures with physical vapor deposition (PVD) titanium aluminum nitride (TiAlN) ceramic-coated tools. The determination of the optimal TiAlN coating thickness is important to obtain superior coating physical properties and decrease the cutting temperature of Inconel 718 alloy.

Objectives: The present study investigates the effects of coating thickness on the physical properties of TiAlN coatings and the cutting temperature during the machining of Inconel 718 alloy. The optimal coating thickness is also determined.

Methods: First, the direct-current-arc method was utilized to deposit PVD Ti_{0.55}Al_{0.45}N coatings with thickness of 1.6 μm, 2 μm, 2.5 μm, and 3 μm, onto a cemented carbide substrate. Second, the coating-thickness-dependent physical properties were characterized and estimated with a radar chart. Third, the effects of coating thickness on coating antifriction were analyzed with the tool-chip friction coefficient when cutting Inconel 718 with PVD TiAlN coated tools. Both the maximum cutting temperature generated in the chip and the cutting temperature of the tool bodies were measured for analysis of the thermal barrier effect of coating. Finally, the topographies of the deformed chip and tool-chip contact area were obtained and investigated to determine the effects of coating thickness on the cutting temperature.
Introduction

Inconel 718 is acknowledged as the representative Ni-based superalloy with a high hardness of 439 HBW and low thermal conductivity of 13.4 W/(m·K) [1]. The massive material deformation energy released during the cutting process is transferred into cutting heat fluxes, resulting in a high cutting temperature during the machining of Inconel 718 alloy [2]. The high cutting temperature induces severe tool wear and reduces the integrity of machined surface. To improve the performance of cutting tools, titanium aluminum nitride (TiAlN) coatings were deposited onto carbide inserts owing to their superior physical properties [3,4]. The main function of this coating is to reduce the cutting temperature during machining operations.

The superior thermal barrier effect of TiAlN coated compared with uncoated tools has been demonstrated. Bogdan-Chudy et al. [5] confirmed that a TiAlN coating (coating thickness of 5 μm) could decrease the internal temperature rise compared with uncoated tools when applying a constant source of 380 °C on the tool rake face in a simulated heating experiment. Akbar et al. [6] used the Abaqus finite element model (FEM) to show that a TiAlN coating (coating thickness of 5 μm) could transfer more heat dissipation from the tool-chip contact interface to the moving chip during the dry turning of AISI/SAE 4140 steel. The cutting temperature was measured by forward-looking infrared (FLIR) thermal imaging camera to confirm the simulation results. Zhao et al. [7] conducted the dry cutting of Inconel 718 with Ti0.4Al0.6N and Ti0.55Al0.45N coated tools (coating thickness of 2 μm). K-type thermocouples were embedded to record the internal temperatures of the tool bodies. The Al content influenced the thermal conductivity of TiAlN coating, thus affecting the coating thermal barrier effects.

The TiAlN coating thicknesses affected the coating thermal barrier and antifriction. Zhao and Liu [8] used the established theoretical model of the monolayer TiAlN coated tool to show that an increase of the coating thickness could improve the thermal barrier. Zhao and Liu [9] utilized a two-color thermometer to measure the cutting temperature in the dry turning of Inconel 718 with TiAlN tools (coating thickness of 1 μm and 2 μm). The thicker coating increased the cutting temperature by approximately 19–30 °C at a cutting speed of 30–120 m/min. Abdoo et al. [10] conducted the dry finish turning experiments of compacted graphite iron (CGI) using Ti0.4Al0.6N coated tools (coating thickness of 5 μm, 11 μm, and 17 μm) with low compressive residual stress coatings deposited by super-fine cathode (SFC) technology. They demonstrated that the coating thickness affected the physical properties of the coating and the antifriction effect significantly. They found that the optimal coating thickness was 10 μm instead of the thickest coating.

The determination of the optimal TiAlN coating thickness is important to obtain superior coating physical properties and decrease the cutting temperature. In this study, the physical properties of PVD Ti0.55Al0.45N coatings with various coating thicknesses were characterized and estimated with a radar chart. The effects of coating thickness on the antifriction effect were analyzed with the tool-chip friction coefficient when cutting of Inconel 718 with PVD TiAlN coated tools. Both the maximum cutting temperature generated in the chip and the cutting temperature of the tool bodies were measured to analyze the thermal barrier effect of coating.

Deposition and characterization of PVD TiAlN coating

Coating deposition

The direct-current-arc method was utilized to deposit a TiAlN coating onto an uncoated carbide tool (NG3189R K313, Kennametal Inc.) [11]. Firstly, the ultrasonic washing procedure was applied to clean the obtained uncoated carbide tools with alcohol and acetone. Massive adhesive impurities and organic impurities on the uncoated tool surface have been cleaned. Then, the H2 and Ar gas were inputted in the cavity with a vacuum 10⁻⁴ mbar and a temperature of 450 °C to remove the oxide layer and imperceptible impurities on the uncoated tool surface before tool coating deposition. Table 1 lists the TiAlN coating deposition conditions. The coating deposition rate was empirically determined as approximately 1 μm/h.

Fig. 1A shows the chemical composition of the TiAlN coating, which was detected as Ti0.55Al0.45N. The fracture cross-section micrographs of the coated tool were obtained by breaking method and scanning electron microscope (SEM) [12]. Fig. 1B shows the fracture cross-section SEM micrographs of TiAlN coated tools with various coating thicknesses.

Characterization

The TiAlN surface roughness was measured with a shape laser microscope (VK-X250K). The TiAlN tool topography and chemical composition were measured by SEM (JSM-6510) coupled with an energy-dispersive spectrometer (EDS). The residual stresses of the TiAlN coating were measured with the sin 2θ method in PANalytical (x-ray diffraction, XRD). The XRD instrument coupling film accessory was utilized together with a grazing incidence module, which can eliminate the substrate effects (incidence angle 0.5°, scanning rate 1 deg/min).

An agilent nano-indentter G200 was used to measure the nanohardness of the coating. The maximum load applied to the three-sided pyramidal Berkovic diamond indenter was 5 mN. The experimental loading and unloading rates were 10.00 mN/min with a duration of 5 s. The coating-substrate adhesion strength was measured by an Anton Paar scratch tester (scratch speed 10 mm/min, load range 1–150 N). More than five measurement experiments of coating nanohardness have been repeated to eliminate the effects of surface roughness on the measurement accuracy of coating nanohardness.

A Dino-Lite microscope was used to observe the width of the tool-chip contact area after the cutting process. The length of the tool-chip contact area lc, deformed chip thickness hc, and the outer surface morphology of the chip were measured with a VK-X250K microscope.

Results: The tool-chip friction coefficient and coating thermal barrier effect were affected by the coating thickness. Ti0.55Al0.45N coated tools with moderate coating thickness had fine antifriction effect with Inconel 718. The thermal barrier effect of Ti0.55Al0.45N coating was positively related to the coating thickness.

Conclusions: The optimal TiAlN coating thickness was determined as 2 μm, which resulted in superior physical properties and reduced the cutting temperature of Inconel 718.
Cutting temperature measurement

Fig. 2A shows a schematic diagram of the cutting temperature when cutting Inconel 718 with the TiAlN coated tool. Fig. 2B presents the experimental setup for measuring the cutting temperature when cutting Inconel 718 with TiAlN coated tools (cutting speed 100 m/min, depth of cut 0.1 mm). The round flakes of Inconel 718 with a thickness of 2 mm were selected, the physical properties of which are summarized in the literature [13].

During the dry orthogonal cutting process, the cutting forces were measured by the three-phase dynamometer Kistler 9129A. The maximum cutting temperature in the cutting zone was measured with the two-color thermometer [14]. The accurate superposition between the clear green spot emitted from the thermometer and the cutting zone was provided by both focusing the thermometer and moving the supported tripod as depicted in the illustration of Fig. 2B and 2C. The infrared energy reflected from cutting zone was captured with the two-color thermometer. The captured infrared energy was transferred into the electric signals related with cutting temperatures by the microprocessor integrated in the thermometer. The variations of the electric signals with time were transformed into the variation of cutting temperature with time by using the built-in software in personal computer. The maximum temperature was then measured in the chip which just flowed from cutting zone and was externally observed. Therefore, the measured maximum cutting temperature in the generated chip can accurately represent the maximum cutting temperature in the cutting zone.

The cutting temperature in the tool bodies was measured by embedded K-type thermocouples combined with the temperature acquisition module OM-DAQ-2401, as shown in Fig. 2D. Owing to the high collection frequency of the temperature acquisition module, many temperature data points were collected by the embedded thermocouple. The fluctuations of these measured data points affected the accuracy of the analysis results. Wavelet packet transform was adopted to filter these fluctuations using MATLAB software. The seven-layer wavelet packet decomposition was carried out, and then the first four layers of high-frequency components were filtered out. Thus, the singular fluctuation points that affect the analysis can be filtered out.

Results and discussion

Surface and microstructure of PVD TiAlN coating

Fig. 3A shows the surface roughness of the TiAlN coated tools with different coating thicknesses. The thicker Ti$_{0.55}$Al$_{0.45}$N coating increased the higher surface roughness. The top view SEM images of cutting tools protected with TiAlN coatings are presented in Fig. 3B. The intermediate and functional layers accounted for the larger thickness ratio of the thin TiAlN coating compared with that for the thick coating. The bias voltages during deposition of the intermediate and functional layers were higher compared with that used during deposition of the surface layer. The attraction of the tool substrate to free Ti and Al ions, and the ion-substrate bombardment were enhanced by the high deposition bias [15]. This enhancement made it easy to break the larger droplets and shock smaller droplets on the surface of the thin tool coating. Therefore, the sizes of white droplets on the TiAlN coatings with thinner coating thicknesses of 1.6 μm and 2 μm were smaller compared with those on coatings with thicknesses of 2.5 μm and 3 μm. The small pits on the surface of the thinner TiAlN coating (coating thickness of 1.6 μm) were attributed to the broken larger droplets and the shocked smaller droplets in Fig. 3B. The massive black spots were detected for the thicker coatings (2.5 μm and 3 μm) in Fig. 3A,

Table 1

| Coating layer | Constant bias voltage (V) | Deposition temperature (°C) | $N_2$ partial pressure (Pa) | Layer thickness (μm) |
|---------------|---------------------------|-----------------------------|-----------------------------|---------------------|
| Intermediate  | −100                      | 500                         | $2-3 \times 10^5$           | 0.2                 |
| Functional    | −40–60                    | 500                         | $2-3 \times 10^5$           | 0.5–2               |
| Surface       | −30–50                    | 500                         | $3-5 \times 10^5$           | 0.2–1               |
Fig. 2. (A) Schematic diagram of the cutting temperature when cutting Inconel 718 with TiAlN coated tools. (B) Experimental setup for cutting temperature measurement. (C) Measurement of maximum cutting temperature in generated chip with two-color thermometer. (D) Measurement of cutting temperature in tool bodies with the embedded K-type thermocouples combined with the acquisition module OM-DAQ-2401.

Fig. 3. TiAlN coated tools with various coating thicknesses: (A) images of coating surface and the sites at which surface roughnesses were measured and marked, (B) Top view SEM images, and (C) XRD analysis.
which were due to the large droplets and pits on the surface of the thick coating (Fig. 3B).

The XRD analysis of the Ti0.55Al0.45N coating with various coating thicknesses is shown in Fig. 3C. The space group of the Ti0.55Al0.45N coating was Pm-3 m (211). The preferential grain orientations of the Ti0.55Al0.45N coating included (111), (200), (220) and (311). The carbide substrate was not well covered by the thin Ti0.55Al0.45N coating (1.6 µm). The diffraction peak of the carbide substrate interfered with the diffraction result of the TiAIN coating. The interference of the diffraction peak was detected near the diffraction angle of 35.5° for the thin Ti0.55Al0.45N coating (1.6 µm). This phenomenon was not observed for the thick Ti0.55Al0.45N coatings in the black dashed square in Fig. 3C(b). Fig. 3C (b) depicts that the diffraction intensity at the preferential grain orientation of (111) has the following sequence: 3 µm > 1.6 µm > 2 µm > 2.5 µm for TiAIN coatings with several coating thicknesses. Fig. 3C(c) and (d) both show that the diffraction intensity at the preferential grain orientations of (200) and (220) has the following sequence: 2.5 µm > 3 µm > 2 µm > 1.6 µm for the TiAIN coating with several coating thicknesses.

**Physical properties of TiAIN coating**

Fig. 4A and 4B show the residual stresses of the Ti0.55Al0.45N coating with various coating thicknesses. The residual stresses on the mutually perpendicular x- and y-directions of the Ti0.55Al0.45N coating were measured as the compressive residual stresses. The resultant residual stress was determined using the square root of the measured residual stresses on the mutually perpendicular x- and y-directions of the Ti0.55Al0.45N coating. The sequence of coating thickness-dependent resultant compressive residual stresses were -1331.72 MPa, -1306.16 MPa, -1159.67 MPa and -683.29 MPa for 3 µm, 2 µm, 2.5 µm and 1.5 µm, respectively. The resultant residual stress of the Ti0.55Al0.45N coating increased by 622.87 MPa (91.16%) when the coating thickness increased from 1.6 µm to 2 µm. The resultant compressive residual stress exceeded -1300 MPa for Ti0.55Al0.45N coatings with coating thicknesses of 2 µm and 3 µm. The high compressive residual stress represented the comprehensive physical properties of the tool coatings [16]. The Ti0.55Al0.45N coatings with thicknesses of 2 µm and 3 µm possessed comprehensive physical properties.

Fig. 4C illustrates the nanoindentation experimental results of the Ti0.55Al0.45N coating with various coating thicknesses. The hardness of the Ti0.55Al0.45N coating increase was with increasing coating thickness. The maximum HIT nanohardness of the Ti0.55Al0.45N coating was 33.41 ± 3.48 GPa at a coating thickness of 2.5 µm.

Fig. 4D shows the scratch test results and scratch morphology of the Ti0.55Al0.45N coating with various coating thicknesses. The critical loads between the tool coating and substrate can be divided into Lc1 and Lc2 according to the ASTM C1624-05 standard. The critical load Lc1 corresponds to the load when the coating starts...
to crack, which indicates a cohesive coating failure. The critical load Lc2 corresponds to the coating crack propagation and the coating edge peeling off, which indicates an adhesion coating failure. The coating-thickness-dependent critical load Lc1 had the following sequence: 2 μm > 3 μm > 2.5 μm > 1.6 μm. The sequence of coating-thickness-dependent critical load Lc1 was similar to that of the measured resultant residual stress for the Ti0.55Al0.45N coating with various coating thicknesses. The superior physical properties of the Ti0.55Al0.45N coating were obtained with coating thicknesses of 2 μm and 3 μm.

The critical load Lc2 of the Ti0.55Al0.45N coating increased with the increase in the coating thickness. The critical load Lc2 of the Ti0.55Al0.45N coating increased by 16.7 N when the coating thickness increased from 1.6 μm to 2 μm. The critical load Lc2 of the Ti0.55Al0.45N coating only increased by 3.4 N when the coating thickness increased from 2 μm to 3 μm. The adhesion force between the TiAlN coating and WC-Co cemented carbide substrate achieved a suitable value at a coating thickness of 2 μm.

Based on the previous experimental results, five evaluation indexes were selected: coating surface roughness, coating resultant compressive residual stress, nanohardness HIT, critical loads Lc1 and Lc2 [17]. The unprofitable index for the improvement of the TiAlN coating was the coating surface roughness; the other four indexes were helpful. The evaluation indexes were standardized with Eqs. (1). The helpful and unprofitable indexes were normalized with Eqs. (2) and (3), respectively.

\[
\bar{X} = \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} \quad (1)
\]

where \(X\) and \(\bar{X}\) are the standard value and measured value of each index. The minimum and maximum values of the same index are \(X_{\text{min}}\) and \(X_{\text{max}}\).

\[
Y = 1 - e^{-\bar{X}} \quad (2)
\]

where \(Y\) is the standardized value of each index.

\[
Y = e^{-\bar{X}} \quad (3)
\]

Fig. 5 depicts the comprehensive radar chart of the Ti0.55Al0.45N coating-thickness-dependent physical properties. It can be seen that the coating thicknesses of 2 μm, 2.5 μm and 3 μm results in superior physical properties compared with a thin coating of 1.6 μm.

Fig. 6A presents the cutting forces when machining Inconel 718 by Ti0.55Al0.45N coated tools with various coating thicknesses. At the cutting speed of 100 m/min, the resultant cutting force of the Ti0.55Al0.45N coated tool with a thin coating of 1.6 μm was higher than that of tools with a thick coating of 2 μm, 2.5 μm, and 3 μm.

There was no obvious difference between the resultant cutting forces of the Ti0.55Al0.45N coated tools with thick coatings of 2 μm, 2.5 μm, and 3 μm.

Fig. 6B illustrates the average tool-chip friction coefficient \(\mu\) determined by Eq. (4) when machining Inconel 718 with Ti0.55Al0.45N coated carbide tools with various coating thicknesses [18]. Compared to the Ti0.55Al0.45N coated carbide tools with coating thicknesses of 1.6 μm and 2.5 μm, a low average friction coefficient could be obtained by Ti0.55Al0.45N coated carbide tools with coating thicknesses of 2 μm and 3 μm. The TiAlN superhard coatings possessed a high nanohardness of approximately 30 GPa, but did not exhibit a decrease in the tool-chip friction coefficient.

\[
\mu = \frac{F_c \sin \gamma + F_r \cos \gamma}{F_c \cos \gamma - F_r \sin \gamma} \quad (4)
\]

where \(\gamma\) is the rake face angle of 0°, and \(F_c\) and \(F_r\) are the average tangential force and radial force, respectively.

**Cutting temperature**

Fig. 7A depicts the maximum temperature of the chip that flowed from the cutting zone when machining Inconel 718 by Ti0.55Al0.45N coated carbide tools with various coating thicknesses. The thicker Ti0.55Al0.45N coating could induce a higher maximum cutting temperature in the generated chip. The maximum cutting temperature in the generated chip increased by 42 °C when the
Ti$_{0.55}$Al$_{0.45}$N coating thickness increased from 1.6 μm to 3 μm. Ti$_{0.55}$Al$_{0.45}$N tools with thicker coating thickness could achieve a lower cutting force and average tool-chip friction coefficient. It was illustrated that a thicker Ti$_{0.55}$Al$_{0.45}$N coating induced more heat dissipation into the flowed chip, thus increasing the maximum cutting temperature in the generated chip.

The TiAlN coating could indicate an evident thermal barrier effect due to its low thermal conductivity of approximately 12.61 W/(m·K) [8]. More heat could be dissipated into the chip that flowed from the cutting zone, thus increasing the maximum temperature of the flowed chip. The thermal barrier effect of the TiAlN coating increased with increasing coating thickness. The maximum temperature of the chip flowed from cutting zone when cutting Inconel 718 by an uncoated carbide tool was 639 °C, which was higher than that by the Ti$_{0.55}$Al$_{0.45}$N coated tools with coating thicknesses of 1.6 μm and 2 μm. Owing to the evident thermal barrier effect of thick TiAlN with coating thicknesses of 2.5 μm and 3 μm, the measured maximum temperature of the chip that flowed from the cutting zone when cutting Inconel 718 with the uncoated carbide tool was lower than that with TiAlN coated carbide tools with coating thicknesses of 2.5 μm and 3 μm.

Fig. 7B shows the measured cutting temperature rise curve of Ti$_{0.55}$Al$_{0.45}$N coated tool bodies with various coating thicknesses during the orthogonal cutting of Inconel 718. The thicker coating could induce a lower temperature at the same point in Ti$_{0.55}$Al$_{0.45}$N coated tool bodies compared with a thin coating. There are two reasons for this phenomenon. First, the thicker Ti$_{0.55}$Al$_{0.45}$N coating prevents the increase of heat dissipation into the tool body. Second, the thicker Ti$_{0.55}$Al$_{0.45}$N coating can induce a greater temperature decrease within the coating thickness. Thus, the internal temperatures of Ti$_{0.55}$Al$_{0.45}$N tool bodies with a thick coating are lower than that of those with a thin coating.

**Topography of tool-chip contact area and deformed chip**

After the orthogonal cutting of Inconel 718 by Ti$_{0.55}$Al$_{0.45}$N coated tools with various coating thicknesses, Fig. 8A and 8B show the width and length of the tool-chip contact area, respectively. Fig. 8C illustrates the deformed chip thickness. The width of the tool-chip contact area for TiAlN coated tools with several coating thicknesses has the following sequence: 1.6 μm < 2 μm < 0 μm < 2 μm.
The length of the tool-chip contact area for TiAlN coated tools with several coating thicknesses has the following sequence: 1.6 μm > 2 μm > 0 μm > 2.5 μm > 3 μm. Compared with the sequence of the cutting temperature, the increase of maximum temperature of the flowed chip might be prevalent with increasing the width of tool-chip contact area and decreasing the length of tool-chip contact area. The deformed chip thickness for TiAIN coated tools with several coating thicknesses has the following sequence: 0 μm > 1.6 μm > 2 μm > 2.5 μm > 3 μm. The deformed chip thickness was mainly dependent on the TiAIN coating thickness in the orthogonal cutting of Inconel 718.

Fig. 9 depicts the outer surface of deformed chip and the deformed chip topography. The thick coating increased the width of the tool-chip contact area, but decreased the length of the tool-chip contact area and the deformed chip thickness. The saw-tooth shape of the deformed chip was induced by the thick TiAIN coating. The thicker Ti0.55Al0.45N coating prevented more heat dissipation into the tool body. The chip was heated and softened because of the heat dissipation into the side of the generated chip. The generated chip could be easily expanded and covered on the tool rake face, thus increasing the width of the tool-chip contact area. In addition, the curvature of the generated chip was decreased after softening, thus decreasing the length of the tool-chip contact area.

The partial peeling of the coating was observed on the rake face of the Ti0.55Al0.45N coated tool with a coating thickness of 3 μm, as shown in the blue circles in Fig. 8B(d). The partial peeling of the coating was not observed on the rake face of the Ti0.55Al0.45N coated tool with coating thicknesses of 1.6 μm, 2 μm, and 2.5 μm. The thicker Ti0.55Al0.45N coating induced a higher cutting temperature and larger temperature gradient within the coating thickness range, which was likely to cause a thermal mismatch between the coating and substrate. A large thermal mismatch could result in the partial peeling failure of tool coatings.

Conclusions

1. The surface roughness of the Ti0.55Al0.45N coating increased with the coating thickness. The sequence of the coating-thickness-dependent resultant compressive residual stress was −1331.72 MPa, −1306.16 MPa, −1159.67 MPa, and −683.29 MPa for 3 μm, 2 μm, 2.5 μm, and 1.5 μm, respectively. The nanohardness of the Ti0.55Al0.45N coating increase was with increasing coating thickness. The maximum HIT nanohardness of the Ti0.55Al0.45N coating was 33.41 ± 3.48 GPa at a thickness was 2.5 μm. The coating-thickness-dependent critical load Lc1 was 2 μm > 3 μm > 2.5 μm > 1.6 μm. The critical load Lc2 of the Ti0.55Al0.45N coating was increased with the increase of coating thickness.

2. The resultant cutting force of the Ti0.55Al0.45N coated carbide tool with a thin coating of 1.6 μm was higher than that of tools with a thick coating of 2 μm, 2.5 μm, and 3 μm. There was no evident difference among the resultant cutting forces of Ti0.55Al0.45N tools with coating thicknesses of 2 μm, 2.5 μm, and 3 μm. Compared to Ti0.55Al0.45N coated carbide tools with coating thicknesses of 1.6 μm and 2.5 μm, a low

Fig. 9. Outer surface topography of the deformed chip after cutting Inconel 718 with Ti0.55Al0.45N coated tools with various coating thicknesses: (A) 1.6 μm, (B) 2 μm, (C) 2.5 μm, and (D) 3 μm.
In summary, the optimal TiAlN coating thickness was determined as 2 \( \mu m \), which resulted in superior physical properties and low cutting temperature of Inconel 718.

Declaration of Competing Interest

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

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