Effect of Boron Nitride Coating on Wear Behavior of Carbide Cutting Tools in Milling of Inconel 718

Halil Caliskan, Bilal Kursuncu, Sevki Yilmaz Guven, Abdullah Cahit Karaoglanli, Mustafa Sabri Gok and Akgun Alsaran

Abstract Boron nitride based tribological coatings promise hope in tribological applications thanks to their excellent lubrication and heat resistance properties. However, the applicability of these coatings on cutting tools in machining applications is not well known and it needs to be revealed. Therefore, in this study, a boron nitride (BN) coating was deposited on carbide milling tools. Inconel 718 was used as workpiece material in face milling tests to determine the wear behavior of the BN coated carbide tools. Surface roughness and tool wear was recorded in relation with cutting length. Wear mechanisms on the coated carbide tools were determined using scanning electron microscopy in combination with energy dispersive spectroscopy. Abrasive and adhesive wear was found as main failure mechanisms on the worn tools. Approximately two times longer tool life was obtained with the BN coated carbide tools.

Keywords Boron nitride coating · Carbide tool · Wear · Inconel 718 · Milling

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H. Caliskan (✉) · B. Kursuncu · A.C. Karaoglanli · M. Sabri Gok
Bartin University, 74100 Bartin, Turkey
e-mail: hcaliskan@bartin.edu.tr

B. Kursuncu
e-mail: bkursuncu@bartin.edu.tr

A.C. Karaoglanli
e-mail: karaoglanli@bartin.edu.tr

M. Sabri Gok
e-mail: msabrigok@bartin.edu.tr

B. Kursuncu · S.Y. Guven
Suleyman Demirel University, 32100 Isparta, Turkey
e-mail: sevkiguven@sdu.edu.tr

A. Alsaran
Ataturk University, 25240 Erzurum, Turkey
e-mail: aalsaran@atauni.edu.tr

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1 Introduction

Inconel 718 superalloy is widely used in high temperature applications such as gas turbines in aviation and aerospace industries [1] since the material has high oxidation and corrosion resistance and it preserves their mechanical properties at high temperatures [2, 3]. Despite these superior properties of Inconel 718, its high wear resistance, deformation hardening and low thermal conductivity cause its machinability to decrease, and Inconel 718 is, therefore, called as difficult-to-cut material [4].

Selection of a suitable cutting tool material has great importance to obtain high performance in machining of Inconel 718 superalloy due to the elevated cutting temperatures and Cr and Ni elements in its chemical composition which make the cutting process difficult [5, 6]. Coated carbide tools are usually substituted for the uncoated one in milling operations of Inconel 718 superalloy due to the fact that thin hard coatings provide superior properties to these tools such as high wear resistance, thermal insulation and/or lubrication. Cutting speeds are restricted for uncoated sintered carbide tools in milling operations of Inconel 718 due to the elevated temperatures [7, 8]. Coating application allows also higher cutting speeds to be used. Different coating layers are deposited on carbide tools for dry and MQCL milling operations of Inconel 718 superalloy in literature, i.e, single layer TiN, TiCN and multilayer TiCN/Al_2O_3/TiN and TiN/TiAlN [8–10]. The diffusion wear mechanism is efficient in milling operations of Inconel 718 with sintered carbide tools due to high cutting temperatures [11]. The diffusion wear can be retarded by low thermal conductivity of the deposited hard coatings and also by low friction coefficient between the coating and chip interface, which reduces cutting temperature relatively.

Boron based tribological hard coatings attract the attention of researchers to be used in tribological applications thanks to their lubrication and heat resistance properties [12, 13]. Due to the limited information on boron nitride coated tools' performance in literature, it is necessary to reveal the applicability of boron nitride coating in milling operations of Inconel 718 superalloy. The goals of this study are to check the wear mechanism of BN coated carbide tools, to measure the lifetime of the tools and to compare the surface roughness of Inconel 718 after milling operations for both coated and uncoated carbide tools.

2 Experimental Set-up

2.1 Workpiece Material

Inconel 718 superalloy was used as workpiece material with dimensions of $150 \times 100 \times 50$ mm and the hardness of $\sim$48 HRC. The material is widely used in aerospace and nuclear industry due to its high temperature strength and high corrosion resistance [1]. The chemical composition of the workpiece material is presented in Table 1. Some mechanical properties of Inconel 718 are also given in Table 2.

Table 1 Chemical composition of Inconel 718 (wt%)

C	Si	Mn	S	P	Ni	Cr	Al	Ti	Nb	Mo	Cu
0.046	0.16	0.18	0.008	0.011	51.34	17.89	0.57	0.99	5.04	3.14	0.031

Table 2 Mechanical properties of Inconel 718

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
1072	1032	0.14

2.2 Cutting Tools and Machine Tool

Uncoated cemented carbide cutting tools (R390-11 T3 08M-KM H13A, Sandvik Company) were used in cutting tests. The tools were positioned on the cutter, supplied from Sandvik Company, with the ISO number of R390-025A25-11L. The tool holder has the cutting diameter of 25 mm and teeth number of 2. In this study, on the purpose to avoid the effect of run-out phenomenon and to maintain constant cutting conditions, only a single tooth was mounted on the cutter during milling tests. Milling operations were carried out on a three-axis Falco VMC 850 CNC vertical machining center.

2.3 Boron Nitride Coating

The boron nitride coating was deposited onto the uncoated carbide tools using a physical vapor deposition (PVD) system (VAKSIS, Turkey) in the Metal Forming Center of Excellence in Atilim University, Turkey. Sintered h-BN was used as target material. The deposition process was carried out in radio frequency magnetron power in a mixture of nitrogen and argon atmosphere. The hardness of the BN coating was measured as 1740 HV using a Fischerscope H100C nanoindenter under a maximum load of 5 mN.

2.4 Cutting Tests

The cutting parameters used in milling tests of Inconel 718 superalloy are given Table 3. The tool wear condition was evaluated using a stereo zoom microscope aided with imaging software. After several cutting distances, the milling tests were stopped and cutting tools were removed from the cutter and mounted to the microscope to measure the wear depth on the cutting tools. Wear images were taken from the flank face of the tool as the dominant wear type is observed as notch wear. The notch wear of 0.8 mm were stipulated as the criterion for tool rejection

Table 3 Cutting conditions

Cutting speed, V_c	30 m/min
Feed rate, f_z	0.05 mm/tooth
Axial depth of cut, a_p	0.1 mm
Radial depth of cut, a_e	15 mm
Workpiece material	Inconel 718
Lubricant	Dry cutting

Fig. 1 Experimental set-up

according to face milling standard (TS ISO 8688-1). Analysis of wear mechanisms was performed using a stereo zoom microscope and then scanning electron microscopy (SEM) (MAIA3 TESCAN) in combination with energy dispersive spectroscopy (EDS). Surface roughness of the machined workpiece was measured with a stylus-type instrument (Mitutoyo Surftest SJ-310). An image of the experimental set-up is given in Fig. 1.

3 Results and Discussion

3.1 Tool Lifetime

Milling tests on Inconel 718 were carried out in dry conditions. Both the BN coated and the uncoted tools were worn by notch wear in the tests. Therefore, the notch wear depth was recorded during the tests. A comparison of lifetime of the BN coated and

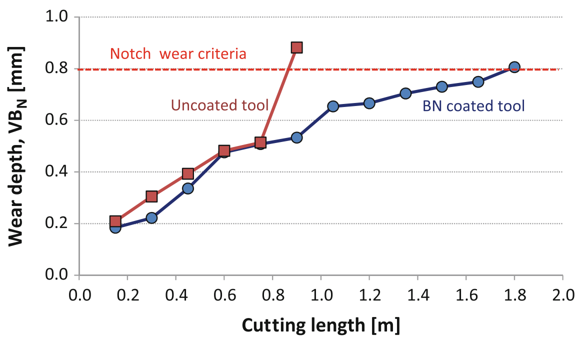

Fig. 2 Comparison of cutting tool lifetime

the uncoated carbide tools as a function of cutting length is given in Fig. 2. As seen from the figure, the BN coating increased the wear resistance and thereby the lifetime of the uncoated tool. The BN deposited coated carbide tool showed approximately a two times longer tool life than the uncoated one. At the initial stage of milling tests, the tools showed almost the same wear depth, and after 0.8 m of cutting length, the uncoated tool reached to the failure zone with a swift increase in wear depth.

3.2 Tool Wear Analysis

Optical microscope images of worn cutting tools are given in Fig. 3. Notch wear, flank wear and build-up edge formation are clearly seen on both the coated and the uncoated tools after milling tests of Inconel 718 superalloy. The notch wear formation is attributed to abrasion mechanism together with oxidation phenomenon at the area where the tool and workpiece material contact finished. Especially the abrasive wear mechanism was dominant on the tool owing to hard carbide particles included in chemical composition of Inconel 718 together with the friction at the tool flank face—the workpiece material interface for both the BN coated and the uncoated carbide tools [11, 14].

In order to perform a detailed investigation on the wear mechanism on the cutting edge, SEM equipment in combination with EDS was used. SEM images of the BN coated and the uncoated tools are given in Figs. 4 and 5, respectively. The dominant failure type for both tools is seen as notch wear as a result of high temperature at the cutting edge in machining of Inconel 718. Oxidation of the cutting tool material at high temperature weakens the cutting edge, and then the abrasive particles in the workpiece lead to abrasive wear of the weak edge. Regular flank wear, chipping and build-up edge formation were also observed for both tools. However, these mechanisms were more severe in the uncoated tool. We can explain the reason of these wear mechanisms in such a way that intermittent cutting in milling operation causes the cutting tool to be exposed to cycling load. These loads lead to stress concentrations at the cutting edge, and thus small fractures occur at the cutting edge and finally the chipping is formed. The reason of build-up edge

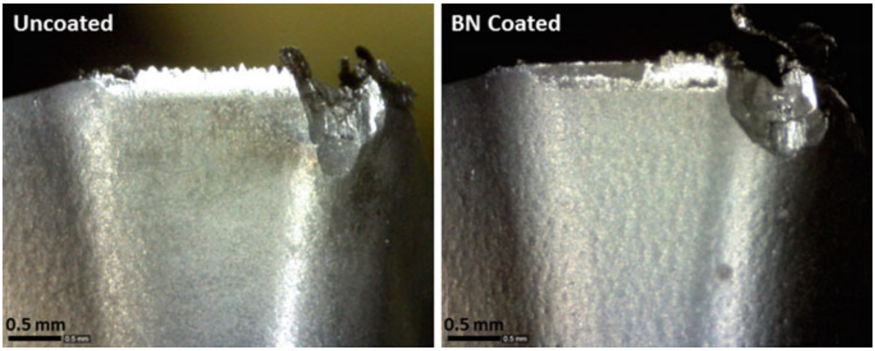

Fig. 3 Tool wear images of worn cutting tools

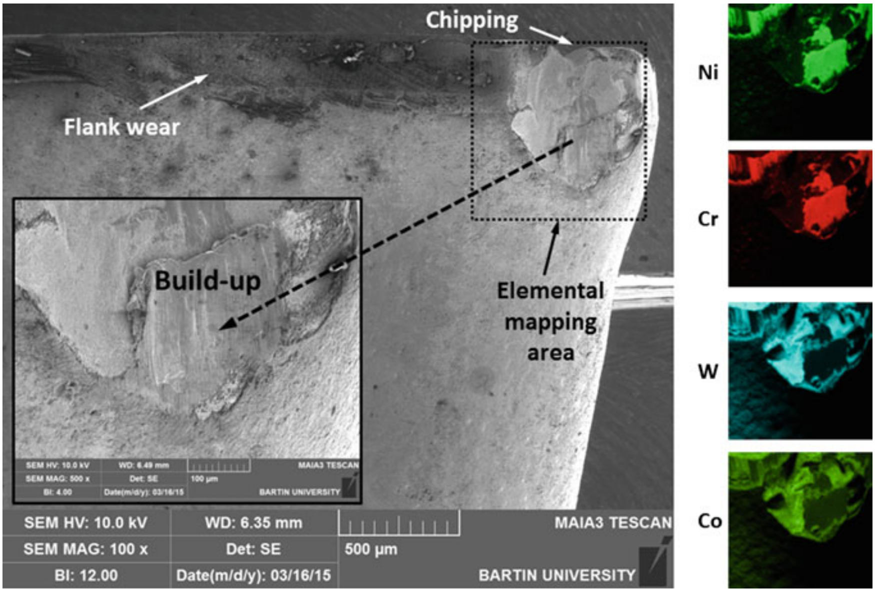

Fig. 4 SEM images and elemental mapping of the worn BN coated tool

formation can be attributed to high cutting temperatures together with high cutting forces. The hardness of the workpiece material at the cutting zone was reduced at high temperatures, and thus sticking/welding of the material on the cutting edge causes adhesive wear [2, 14, 15]. The build-up edge formation is confirmed also by elemental mapping as seen in Fig. 4. Ni and Cr elements confirm the existence of the workpiece material Inconel 718 at the cutting edge, on the other hand W and Co is coming from the carbide cutting tool material. When compared to the uncoated tool, the lower amount of notch wear and build-up formation is thought to be obtained by BN coating's lubricant property.

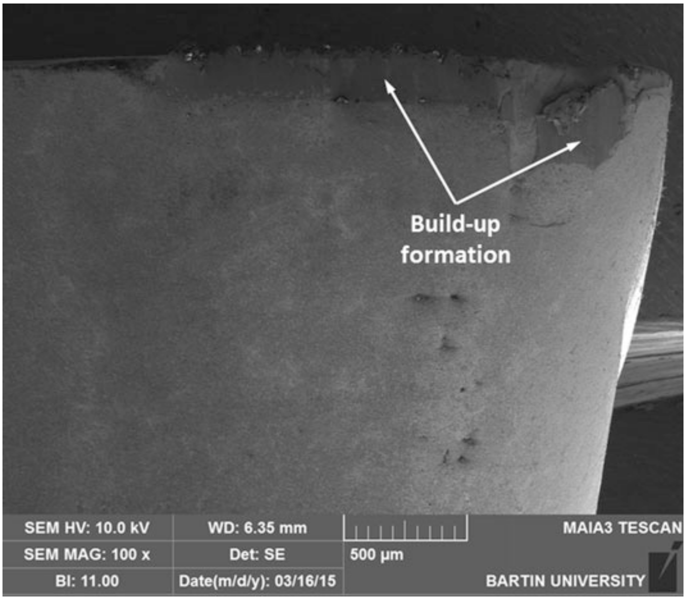

Fig. 5 SEM images of the worn uncoated tool

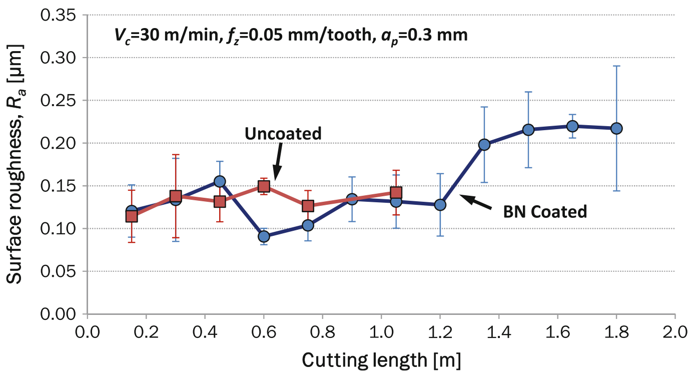

Fig. 6 Surface roughness data of the machined Inconel 718 as a function of cutting length

3.3 *Evaluation of Surface Roughness*

The surface roughness of the workpiece material machined by the BN coated and the uncoated tools are compared in Fig. 6. The roughness of the machined surface was observed to be lower than 0.25 μm for both the uncoated and the BN coated tools after milling process. The surface roughness obtained with the BN coated tools was almost lower than the uncoated one. The roughness of the machined surface of Inconel 718 superalloy during milling process was seen to be not significantly affected by tool wear. The surface roughness was similar in the steady state wear region (up to 1.2 m), while a higher roughness (R_a of $\sim$0.22 μm) was obtained with the BN coated carbide tool after the cutting length of 1.2 m. The increase in the roughness can be attributed to the increase of build-up edge formation and the damage of the cutting edge [16].

4 Conclusions

In this research, the influence of the BN coating on the wear behavior of carbide cutting tools in face milling of the Inconel 718 superalloy was investigated. Also, the roughness of Inconel 718 superalloy was investigated during milling tests. The main results can be summarized as follows:

- The BN coated tools outperform uncoated carbide tools by $\sim$100 % in terms of maximizing the tool life, which is a promising result for using the BN in milling process of Inconel 718 superalloy.
- The main wear modes on the BN coated and the uncoated tools were abrasion and adhesion wear. Dominant tool failures were notch wear, flank wear, build-up edge and chipping.
- The BN coating has no significant effect on the surface roughness of Inconel 718 in milling tests.

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