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ORIGINAL ARTICLE

Improvement of cutting performance of carbide cutting tools in milling of the Inconel 718 superalloy using multilayer nanocomposite hard coating and cryogenic heat treatment

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Abstract

In this study, milling of the Inconel 718 superalloy was performed in dry conditions with the aim of reducing the adverse effects of the coolant on the environment. As is known, cutting tools quickly complete their life due to the high-temperature on the cutting zone in the dry condition milling process of hard materials. The nanocomposite TiAlSiN/TiSiN/TiAlN thin film was deposited on the cutting tools and then subjected to cryogenic heat treatment to increase the tool life of the used cutting tools. As a result, the life of the cutting tools has been increased by the thin film coating and cryogenic heat treatment applied to the cutting tools. After cryogenic treatment at a cutting speed of 30 m/min, the tool life of uncoated, TiN-, nanocomposite TiAlSiN/TiSiN/TiAlN-, and TiAlN-coated carbide cutting tools increases by 54, 110, 29, and 30%. The applied cryogenic heat treatment resulted in an 18% increase in the hard η phase of the structure of the carbide cutting tools. In addition, cryogenic heat treatment improved the adhesion of hard coatings to the substrate. The EDS analysis applied to the worn tools revealed that the mechanisms causing wear of the cutting tools were abrasion and adhesion.

Keywords Inconel 718 · Carbide cutting tool · Hardmilling · Cryogenic heat treatment · Nanocomposite hard coatings

1 Introduction

The Inconel 718 nickel-based superalloy is used in the production of nuclear reactors, spacecrafts, rocket motors, gas turbines, and pumps due to its high corrosion resistance, excellent creep rupture strength at elevated temperatures, and its high ratio of strength to weight [1–8]. Besides, the Inconel 718 superalloy is known as a hard-to-cut material due to its low thermal conductivity, high hardness at elevated temperatures, high chemical affinity, and work hardening tendency [9–11].

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Therefore, milling of the Inconel 718 superalloy even at high feed rates and cutting speeds is very hard due to high temperatures and high cutting forces generating at the cutting zone. This causes an extremely short tool life, low productivity, and deteriorates surface quality in milling Inconel 718 [12–14]. In addition, chips welding on the tool faces form a built-up edge (BUE) and then because of peeling from these chips with coating or tool material, a damage called chipping occurs on the tools. Therefore, the selection of an appropriate cutting tool and coating material is very crucial in machining operations of the Inconel 718 superalloy [15–17]. Requirements for cutting tool and coating materials for a high-performance face milling process of this superalloy are high hardness, high strength and wear resistance, high red hardness and toughness, high thermal conductivity and specific heat capacity, low coefficient of friction, and chemical stability. For this reason, in order to obtain a good workpiece surface condition and an acceptable tool life, all the cutting parameters such as cutting speed and feed rate must be conveniently selected while machining the Inconel 718 superalloy [18–20].

Different methods are used to increase the life of the cutting tools and to minimize the environmental damage

Table 1 Mechanical properties of Inconel 718

Yield strength	Tensile strength	Elongation
1072 MPa	1032 MPa	0.14%

of the manufacturing process and to reduce the cutting tool cost. Some of these methods are dry machining [21], determining the optimum cutting parameters [22], depositing hard coatings on cutting tools [23], minimum quantity lubrication method [24], and cryogenic heat treatment to cutting tools [25]. The sintered carbide cutting tools are typically preferred in the milling of the Inconel 718 superalloy. In order to achieve a longer tool life and higher tool performance, hard coatings are deposited on carbide tools [26, 27]. As known, coating deposition is performed to increase wear resistance of the carbide tool, to reduce friction on the cutting zone, and thus to reduce the temperature in the cutting zone simultaneously [9, 28]. Thin hard coatings deposited onto the tool surface can improve the resistance towards abrasion, adhesion, diffusion, and oxidation wear mechanisms. Bhatt et al. [29] deposited single-layer TiAlN by the physical vapor deposition (PVD) process and triple-layer TiCN/Al_2O_3/TiN composite coating by the chemical vapor deposition (CVD) process on carbide tools to improve their wear resistance while machining the Inconel 718 superalloy. Composite TiCN/Al_2O_3/TiN-coated carbide tools showed a superior wear resistance at high cutting speeds. Devillez et al. [30] used AlTiN-coated carbide tools for machining the Inconel 718 superalloy and obtained better tribological behavior when compared to TiAlN-coated carbide cutting tool. Park et al. used TiAlN- and TiCN-coated and uncoated cemented carbide cutting tools together with minimum quantity lubrication for milling the Inconel 718 superalloy and found that the coated inserts showed a longer tool life.

Table 3 The parameters used in cutting tests

Cutting parameter	Level		
	1	2	3
V_c, cutting speed (m/min)	20	30	40
f_z, feed rate (mm/tooth)	0.05		
a_p, axial depth of cut (mm)	0.2		
a_e, radial depth of cut (mm)	15		

Sintered carbide cutting tools are manufactured by placing the hard tungsten carbide particles in a cobalt metal matrix. As a result, a composite material with superior properties is obtained. Compared to other cutting tool materials, they are often preferred due to their excellent abrasion resistance, hardness, and manufacturability in complex geometries [31]. Due to the high temperatures that occur during the processing of hard materials, cutting tool materials quickly complete their life. In order to prolong the tool life of carbide cutting tools is the cryogenic

Table 2 Chemical composition of Inconel 718 (wt%)

C	Si	Mn	S	P	Ni	Cr	Al	Ti	Nb	Mo	Cu
0.045	0.15	0.17	0.007	0.012	51.35	17.87	0.56	0.98	5.03	3.12	0.032

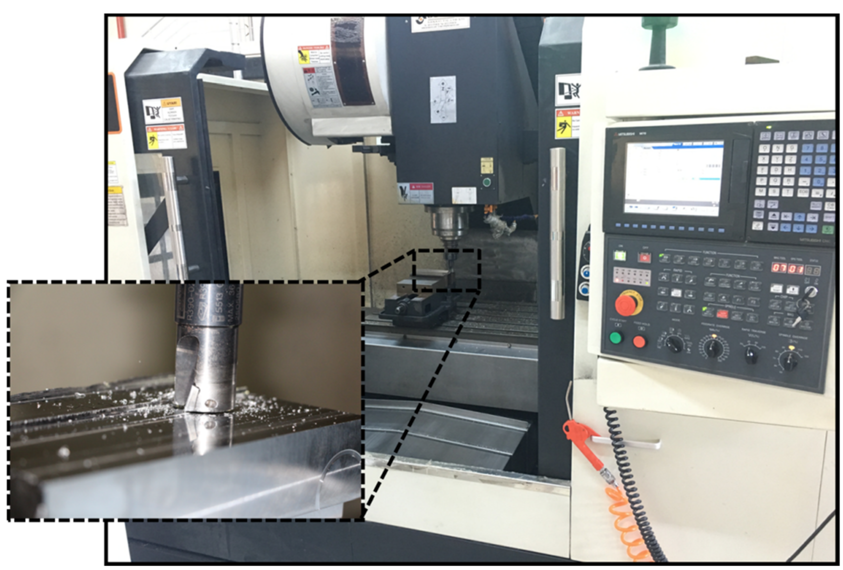


Fig. 1 Falco VMC 855-B CNC machining center

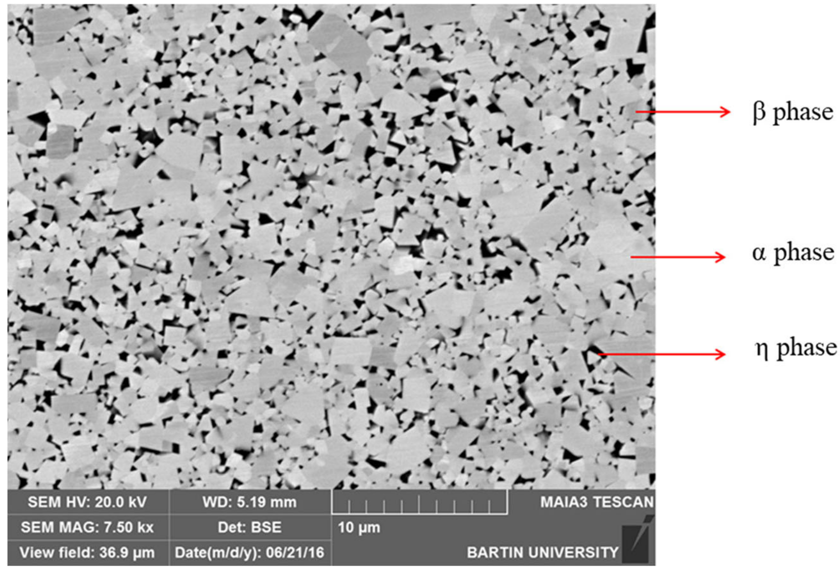


Fig. 2 The microstructure of carbide cutting tool

treatment, which is a heat treatment applied well below room temperature [32–34]. Nitrogen and helium gases are used in cryogenic treatment for gradually cooling (2 °C/min) of samples down to temperatures varying from − 80 to − 196 °C and holding a period (18 to 36 h) at these temperatures and gradually brought back to the room temperature [32, 35–37]. The cryogenic heat treatment ensures that the carbides in the metal matrix have a more stable structure. The cryogenic heat treatment changes the cobalt phase or crystal structure in the metal matrix and increases the resistance to different loads during cutting. The increase in strength of the tungsten carbide cutting tools can be attributed to the increase of the η-phase in the metal matrix. Although the η-phase in the metal matrix is harder than the other phases, it negatively affects the toughness of the material. Therefore, to achieve optimum conditions, it is necessary to adjust the change in the η-phase well. In addition, the cryogenic heat treatment also provides for the regulation of the internal stresses that occur during manufacturing of tungsten carbide cutting tools [34, 38–40]. The properties of carbide tools such as electrical conductivity, hardness, abrasion resistance, and toughness can be improved via cryogenic treatment in consequence of homogenization of the carbide particles distribution [32]. Thanks to cryogenic treatment, the cutting performance of carbide tools can be improved by decreasing tool wear and cutting forces, increasing tool life and providing a good surface integrity in the workpiece material [41–43]. Seah et al. demonstrated that the tool life of carbide tools at high speeds turning process of carbon steel can be improved [44]. Gill et al. declared that, after cryogenic treatment, carbide cutting tools have better mechanical properties than the untreated one [45]. Reddy et al. showed that cryogenically treated carbide cutting tools exhibited a longer tool life and a lower cutting force than the untreated one while machining of C45 steel [46].

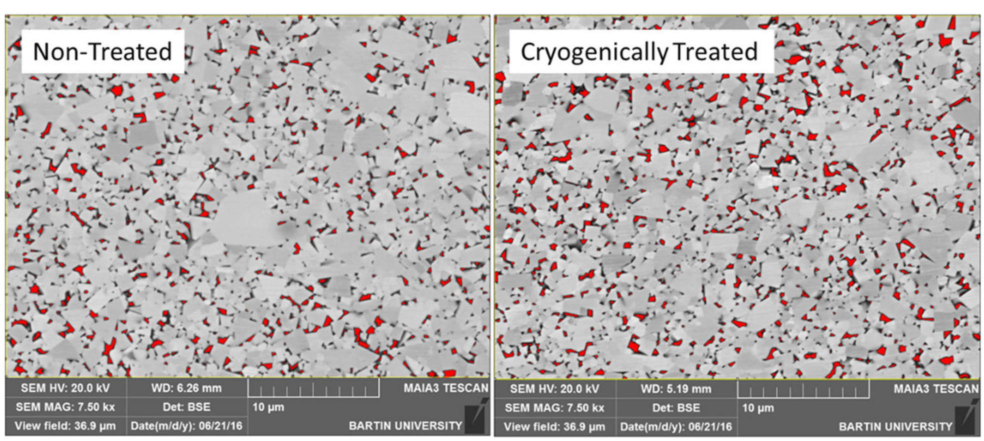


Fig. 3 Image analysis of carbide cutting tools

Table 4 The critical load (LC3) obtained with scratch test

Coating	LC3 (*N*)
TiN	28
TiAlN	30
NC	43
Cryo-TiN	50
Cryo-TiAlN	70
Cryo-NC	80

The study on milling the Inconel 718 superalloy using cryogenically treated carbide cutting tools is very limited [30]. For this reason, this work has the aim of to show the effect of cryogenic treatment together with hard thin hard coating on the cutting performance of carbide cutting tools while face milling operation of the Inconel 718 superalloy workpiece material. After the milling process, the surface roughness values are also evaluated in this paper. In addition, the effect of cryogenic heat treatment on the adhesion of the hard coatings to the substrate and the internal structure of the carbide cutting tools was also investigated.

2 Materials and methods

2.1 Workpiece material

The Inconel 718 super alloy was selected as the workpiece material. The hardness of the workpiece material was measured as ~ 48 HRC. Table 1 and Table 2 show some properties and chemical composition of the Inconel 718 workpiece material.

2.2 Experimental setup

Uncoated carbide cutting tools (R390-11 T3 08M-KM H13A Coromill 390) and tool holder (R390-025A25-11L Coromill 390) used in the milling process were supplied from the Sandvick Company. The tool holder used in the milling test has two mouths on which the cutting tool can be placed, but only one mouth was placed with a cutting tool, due to in order to prevent formation of run-out phenomenon on the cutting tool. Milling tests were performed on a three-axis CNC (Falco VMC850 CNC) (Fig. 1).

2.3 Coating and cryogenic treatment of cutting tools

Thin hard film nc-TiAlSiN/TiSiN/TiAlN coating (NC) was applied with CemeCon CC800/9 sinOx ML PVD coating center to increase abrasion resistance of cutting tools. The detailed information on the coating applied to the cutting tools is given in reference [31]. TiN and TiAlN single-layer thin hard film coatings were applied in order to compare the performance of the obtained NC hard thin film coating. After the coating deposition process, cryogenic treatment was applied to the cutting tools at a temperature of − 145 °C for 24 h. Cooling and heating speeds of cryonic treatment is 2 °C/min. After cryogenic treatment, the tools were

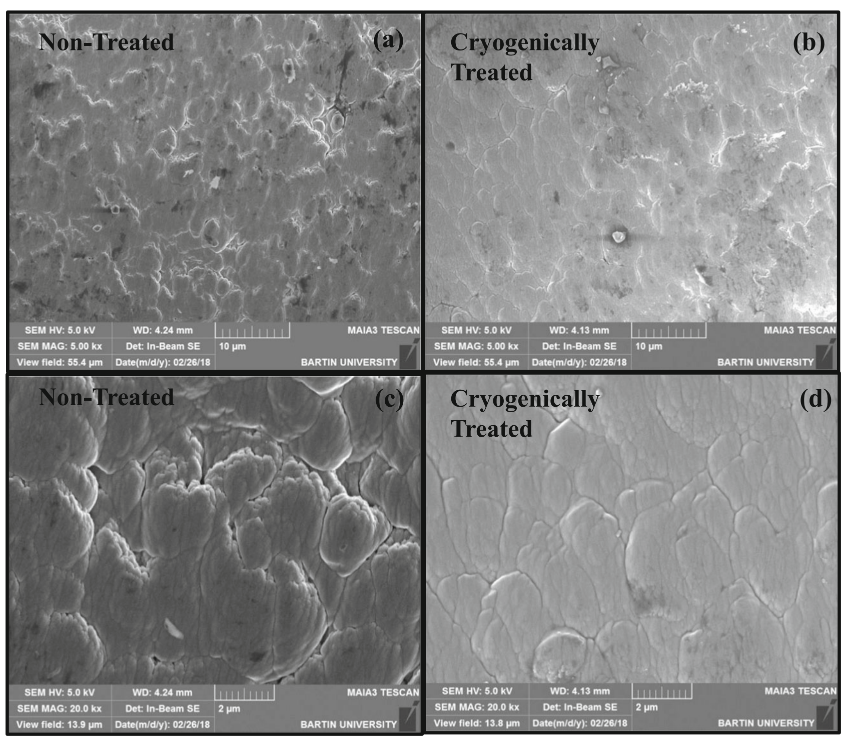


Fig. 4 SEM images of NC coatings in the case of non-treated (a), cryogenically treated (b) for 5 kx magnified and non-treated (c) cryogenically treated (d) for 20 kx magnified

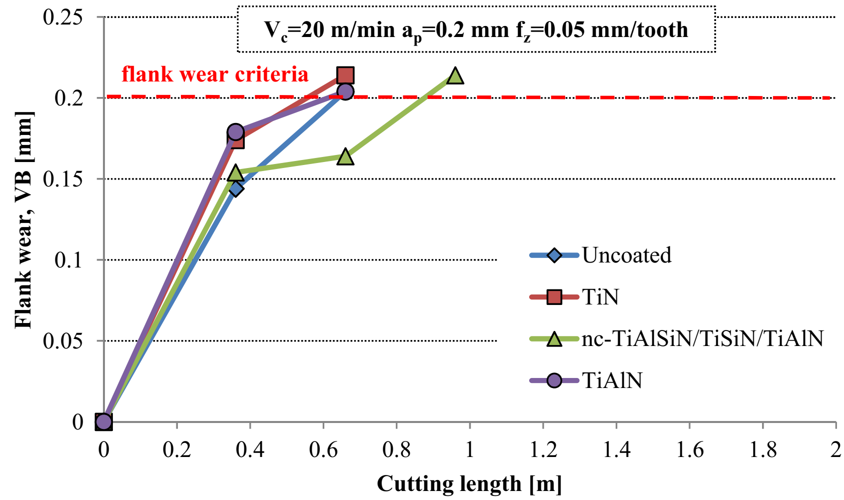


Fig. 5 Tool life of the non-treated carbide cutting tools at cutting speed of $V_c = 20$ m/min

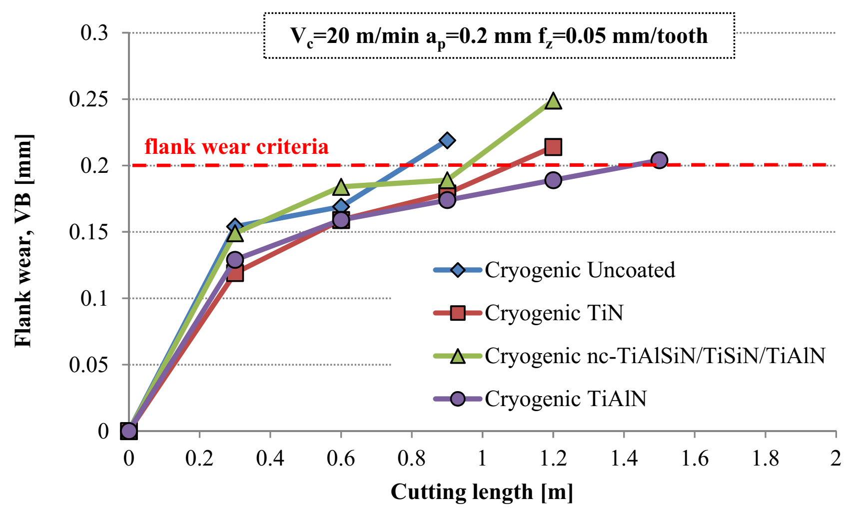


Fig. 6 Tool life of the cryogenically treated carbide cutting tools at cutting speed of $V_c = 20$ m/min

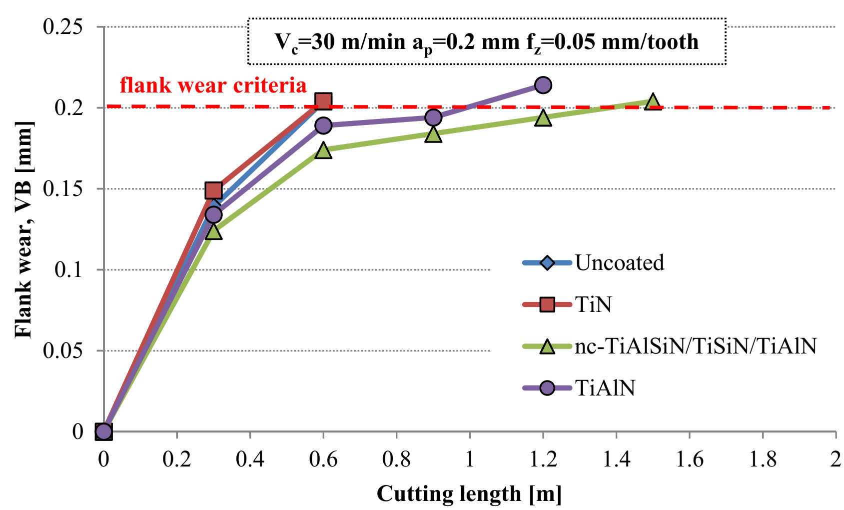


Fig. 7 Tool life of the non-treated carbide cutting tools at cutting speed of $V_c = 30$ m/min

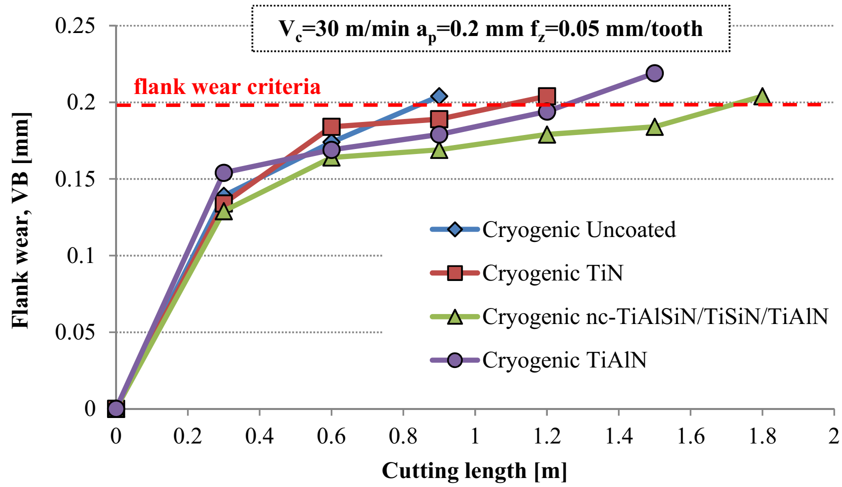


Fig. 8 Tool life of the cryogenically treated carbide cutting tools at cutting speed of $V_c = 20$ m/min

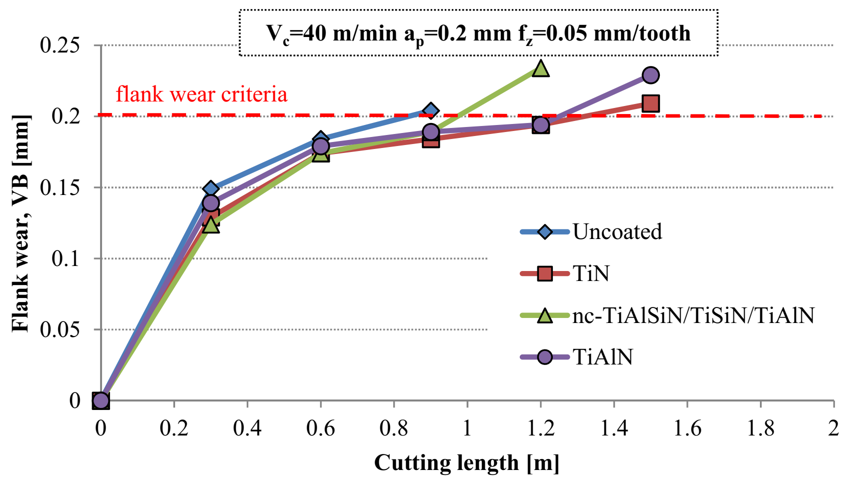


Fig. 9 Tool life of the non-treated carbide cutting tools at cutting speed of at cutting speed of 40 m/min

tempered at 200 °C for 2 h. Adhesion strength of the coatings to steel substrates was measured using a CSM Revetest scratch tester with a scratch length of 3 mm, a maximum load of 150 N, a loading rate of 200 N/min, and a stylus speed of 4 mm/min.

2.4 Cutting tests

The milling tests were performed at dry condition with the Inconel 718 superalloy workpiece. Table 3 shows the cutting parameters. The cutting speed ranges from 20 to 30 m/min,

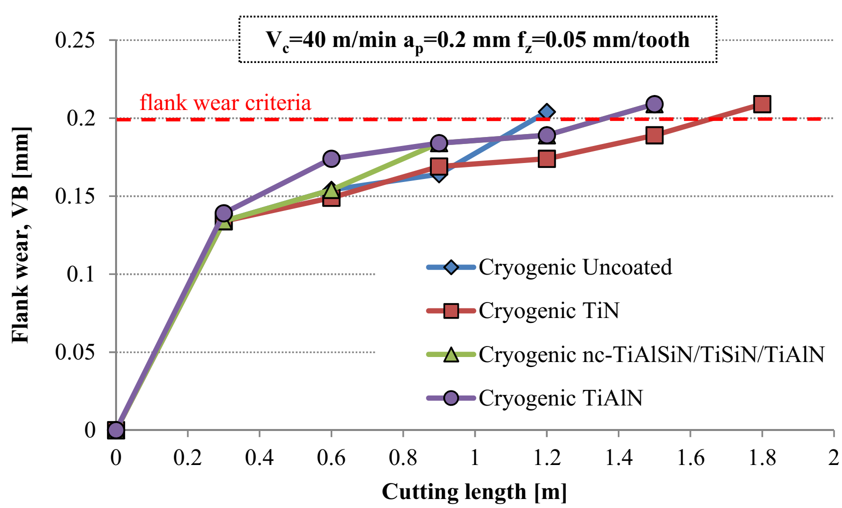


Fig. 10 Tool life of the cryogenically treated carbide cutting tools at cutting speed of 40 m/min

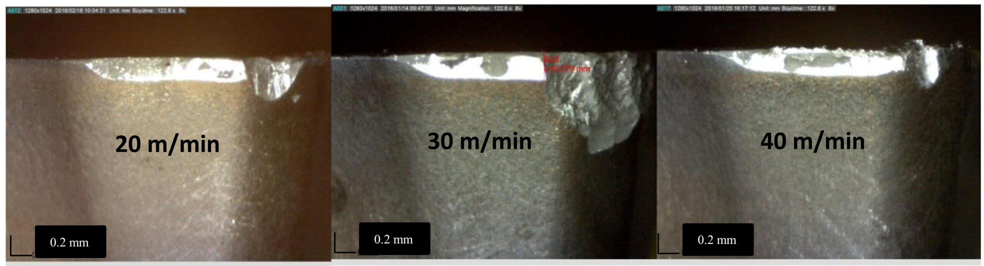


Fig. 11 Optical microscopy images of non-treated NC coated worn cutting tools

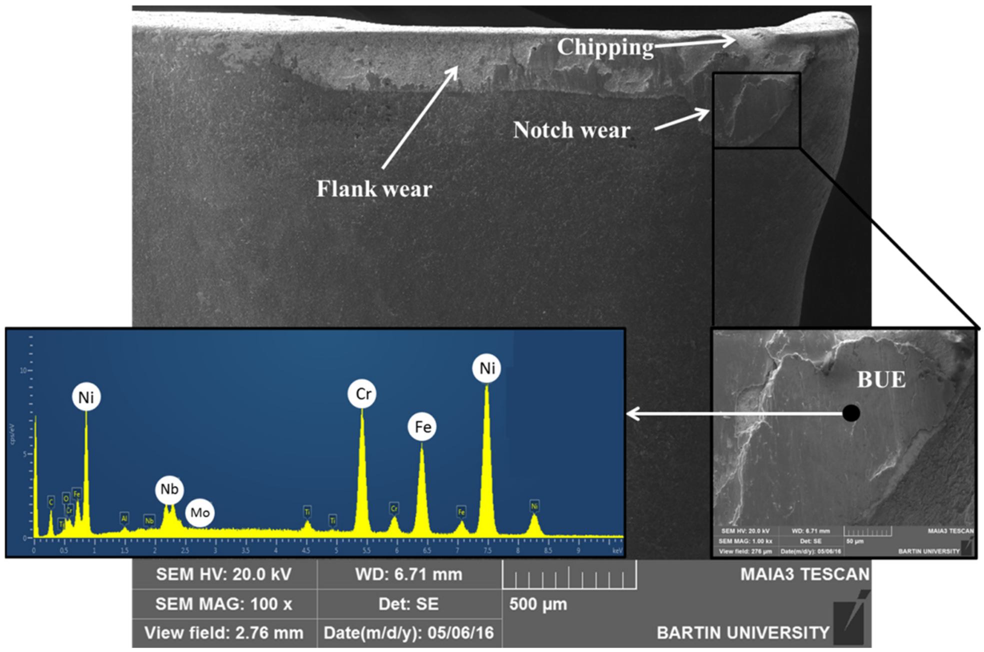


Fig. 12 SEM photo and EDS analysis of the non-treated NC coated worn tool at 20 m/min cutting speed

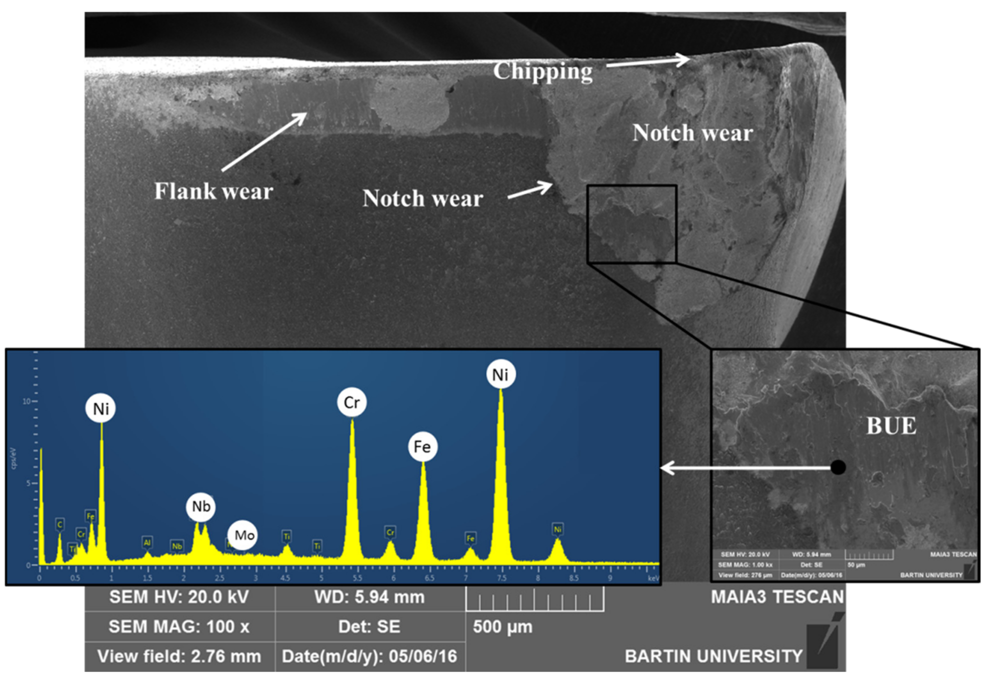


Fig. 13 SEM photo and EDS analysis of the non-treated NC coated worn tool at 30 m/min cutting speed

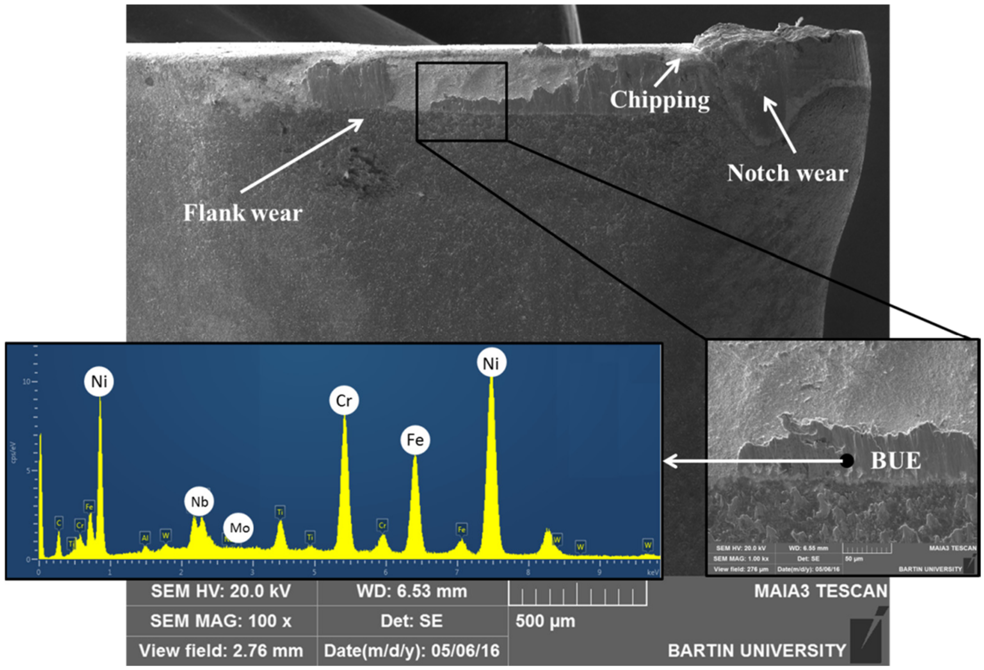


Fig. 14 SEM photo and EDS analysis of the non-treated NC coated worn tool at 40 m/min cutting speed

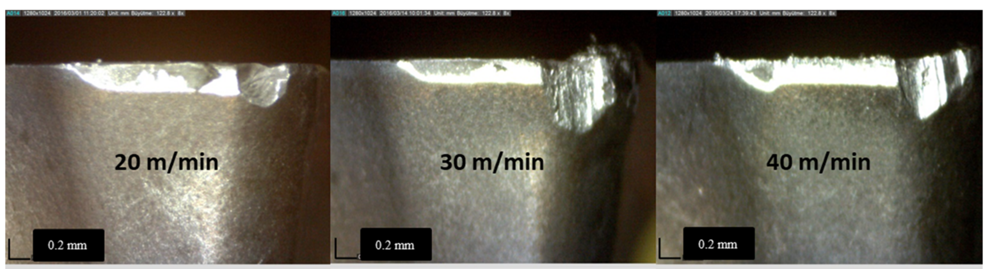


Fig. 15 Optical microscopy images of cryogenically treated NC coated worn cutting tools

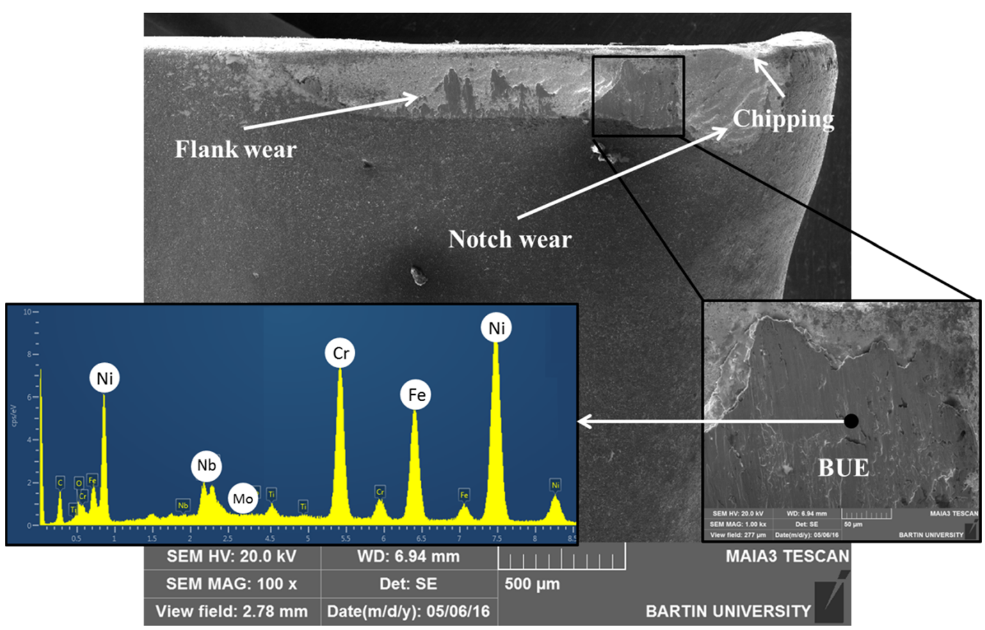


Fig. 16 SEM photo and EDS analysis of the cryogenically treated NC coated worn tool at 20 m/min cutting speed

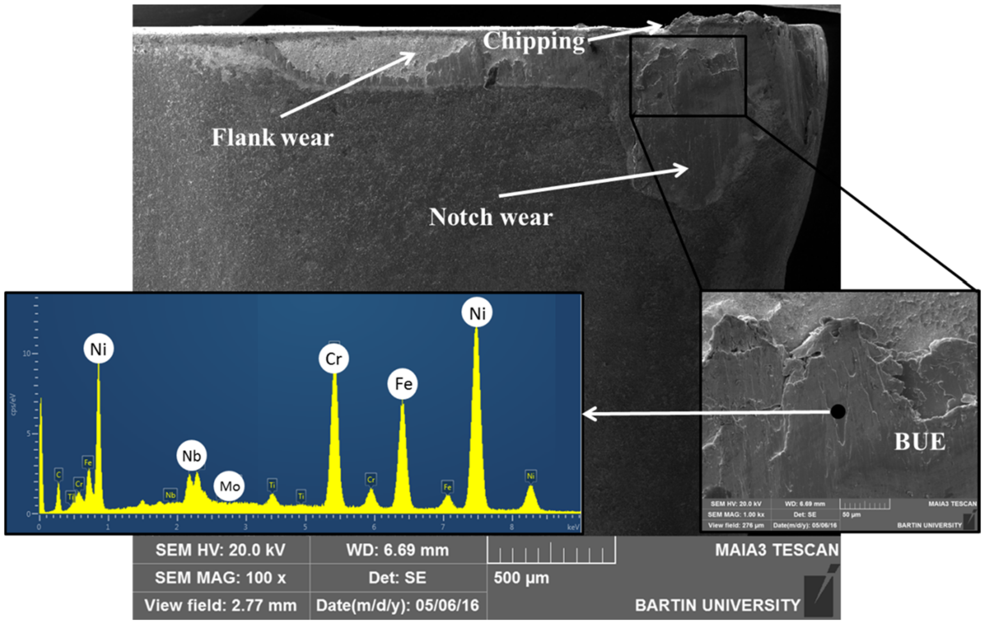


Fig. 17 SEM photo and EDS analysis of the cryogenically treated NC coated worn tool at 30 m/min cutting speed

while axial and radial depths of the cut were fixed. Surface milling operations were performed on the 150-mm-long edge of the workpiece. In the process of determining the amount of tool wear, a software-aided stereo zoom microscopy was used. After each 300-mm milling operation, the cutting tool was removed from the tool holder and the amount of wear was measured with a stereo zoom microscope. Flank wear was observed as a dominant type of wear. According to the TS ISO 8688-1 milling standard, if the flank wear reaches a length of 0.2 mm, the cutting tool was considered worn. A scanning electron microscope (SEM) (MAIA3 TESCAN) in combination with energy dispersive spectroscopy (EDS) was used to investigate the wear mechanisms of the cutting tool in detail. Mitutoyo Surftest SJ-310 was used to determine the roughness values of the machined surface.

3 Results and discussion

3.1 Effect of cryogenic heat treatment on the microstructure of the cutting tool and on the coating adhesion strength

Figure 2 shows the microstructure and different phases of the carbide cutting tool. As is known, sintered carbide materials

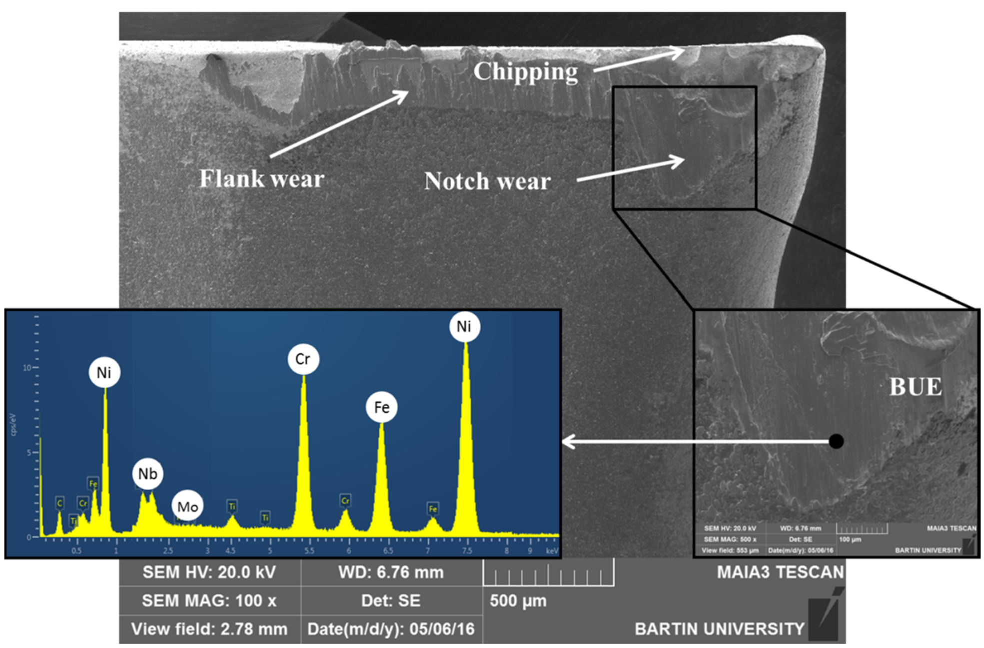
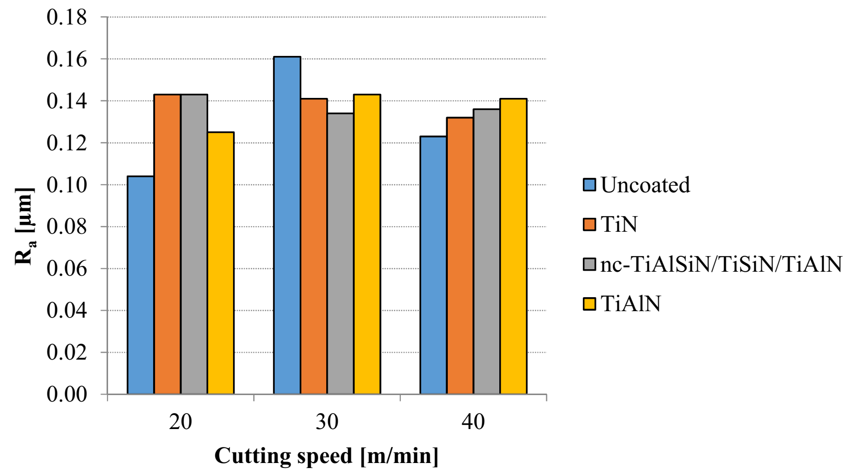


Fig. 18 SEM photo and EDS analysis of the cryogenically treated NC coated worn tool at 40 m/min cutting speed

Fig. 19 Surface roughness of the workpiece material obtained with non-treated cutting tools



have three different phases. These are α (WC), β (Co), η (Co_3W_3C, and Co_6W_6C).

Figure 3 illustrated image analysis of carbide cutting tools. The phase indicated in red in the figure belongs to phase η. In the analysis of the obtained SEM images, the amount of the η phase in the total area on the image taken from three different places through the samples was calculated and the averages of the obtained percentage ratios were taken. Accordingly, the η phase increased by approximately 18% due to the cryogenic heat treatment. This increase indicates a change in the microstructure of the material by cryogenic heat treatment. Similarly, Özbek et al. [47] observed an increase of approximately 11% in phase η by cryogenic heat treatment with carbide cutting insert.

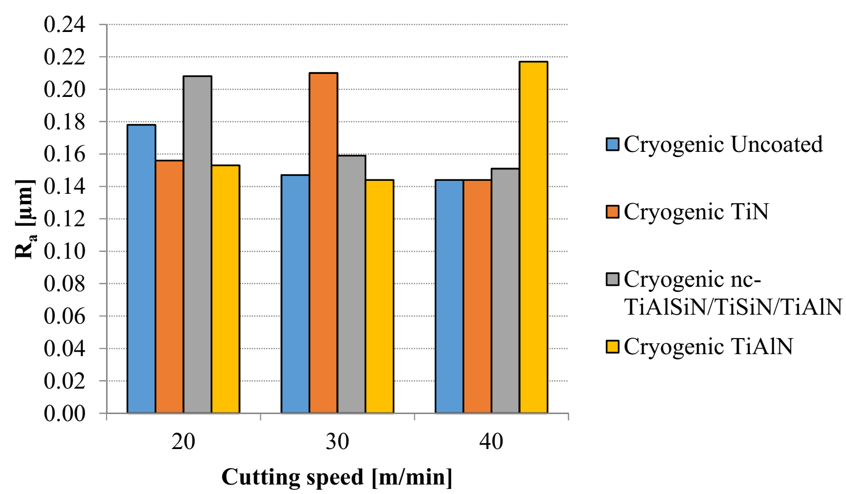
Table 4 shows the LC3 critical load values obtained from the scratch test of different treated and non-treated coatings. The LC3 critical load value determines the point at which the coating flaking is first observed, and this value is determined by examining the optical images and the acoustic emission values [48]. According to these obtained values, the best adhesion property to the substrate was obtained with NC coating. According to these results, the cryogenic heat treatment applied to the hard coatings resulted in an increase in the adhesion of the coatings to the substrate material. Therefore, it can be said that the increase of the adhesion of hard coatings to the base material increases the tool life of cutting tools in the milling process. Similar result was obtained by Chetan et al. [49].

In Fig. 4, SEM images of cryogenically treated and non-treated NC hard coatings are seen at different magnifications. It can be said that the increase in abrasion resistance of hard-coated carbide cutting tools is due to the more homogeneous and smooth structure that occurs due to the applied cryogenic heat treatment [49].

3.2 Tool lifetime

Figures 5 and 6 show the obtained tool life of the non-treated and cryogenically treated carbide cutting tools, respectively, at cutting speed of $V_c = 20$ m/min. As clearly seen from Fig. 5, single-layer coated and uncoated carbide cutting tools gave nearly similar tool lifetime. The NC-coated tool outperformed the others with ~1.15 times longer lifetime. According to Fig. 6 drawn for cryogenically treated carbide cutting tools'

Fig. 20 Surface roughness of the workpiece material obtained with cryogenically treated cutting tools



lifetime, the longest tool life was reached with the cryogenically treated single-layer TiAlN-coated carbide cutting tool with cutting length of ~ 1.4 m. All cryogenically treated carbide cutting tools gave a longer tool life than the non-treated tools at the same cutting conditions. The influence of cryogenic heat treatment on the single-layer TiN- and TiAlN-coated carbide cutting tools was nearly two times longer tool life when compared to the non-treated cutting ones. Thamizhmanii et al. used cryogenically treated carbide inserts in milling operation of the Inconel 718 superalloy, and they reported that a longer tool life is possible with cryogenic heat treatment [50]. Similarly, Yong et al. obtained 33% longer tool life using cryogenically treated carbide cutting tools than the untreated one in milling of carbon steel [51].

Figures 7 and 8 show the obtained tool life of the non-treated and cryogenically treated carbide cutting tools, respectively, at cutting speed of $V_c = 30$ m/min. The non-treated NC-coated carbide cutting tool demonstrated a longer tool life than the others as seen in Fig. 7. TiN-coated and uncoated carbide cutting tool gave a similar tool life (0.6 m). The TiAlN-coated carbide cutting tool has a tool life of 1 m cutting length.

As seen from Fig. 8, at 30 m/min cutting speed, cryogenically treated cutting tools gave a longer tool life than the non-treated ones. The tool life of uncoated, TiN-, NC-, and TiAlN-coated carbide cutting tools increased by 54, 110, 29, and 30%, respectively, after cryogenic heat treatment. Cryogenically treated NC-coated tool exhibited the longest tool life (1.8 m) compared to the other tools.

Figures 9 and 10 show the obtained tool life of the non-treated and cryogenically treated carbide cutting tools, respectively, at cutting speed of $V_c = 40$ m/min. Non-treated TiN- and TiAlN-coated tools gave a better tool life (1.3 m) than the NC-coated one (1.0 m). At the initial stage of the milling test, wear propagation was the same for all tools as seen in Fig. 9.

As seen in Fig. 10, TiN-coated and cryogenically treated carbide cutting tool gave the best tool life (~ 1.7 m) compared to the other cutting tools. At a cutting speed of 40 m/min, the cryogenically treated TiAlN-coated carbide cutting tool exhibited a similar tool life with the non-treated one. Tool life of the tools, except the TiAlN-coated one, was improved by cryogenic heat treatment.

3.3 Tool wear analysis

The images of the NC-coated worn cutting tools are shown in Fig. 11. Built-up edge, flank wear, and notch wear formation are seen on the worn tools. Detailed analysis on wear type and wear mechanisms were performed through scanning electron microscopy (SEM) in aided with EDS. Through evaluation of EDS results and SEM images, built-up edge, flank wear, notch wear, and chipping were described on the worn tools.

SEM images of non-treated nanocomposite coated carbide tool achieved at cutting speeds of 20, 30, and 40 m/min are presented in Figs. 12, 13, and 14, respectively. Tool wear is caused by the effect of abrasion wear mechanism, which is thought to be due to the hard carbide particles in the workpiece chemical composition. It is thought that flank wear, which is seen in all cutting tools, is caused by high temperature and abrasion wear mechanism. It is followed by notch wear. Other wear types seen on the cutting tool are chipping and BUE. It is thought that the notch wear at the edge of the cutting tool is arising from the abrasive effects of the hard carbide particles in the workpiece chemical structure at the weakened end due to the oxidation and diffusion wear mechanisms. Dynamic cutting forces generating during the non-continuous cutting process in face milling was thought to be a reason of chipping wear observed on the tools. Built-up edge formation was attributed to high cutting forces and high cutting temperatures occurring during the cutting process. In addition, welding of the workpiece on the tool flank face (seizure formation) was observed, and its formation increased with the increment of cutting speed. This was ascribed to the increasing temperatures at higher cutting speeds [9, 48, 52].

Optical microscopy images of cryogenically treated NC-coated worn tools for different cutting speeds were given in Fig. 15. After a detailed analysis on the worn tools by SEM in combination with EDS (Figs. 16, 17, 18), it was seen that wear types and mechanisms in case of cryogenic heat treatment are similar to non-treated tools, i.e., built-up edge formation, flank wear, notch wear, sticking zone, and chipping wear. In addition, it was recognized from the SEM images that the intensity of the built-up edge increased with the cutting speed.

3.4 Surface roughness

Surface roughness values (R_a) obtained by both non-treated and cryogenically treated cutting tools are presented in Figs. 19 and 20, respectively. It is seen that surface roughness commonly increased with cryogenically treated tools at all cutting speeds although it is still under 0.22 μm, which proves that surface quality is acceptable in finish milling. The NC-coated carbide cutting tools gave a good surface quality at cutting speeds of 30 and 40 m/min. There is no clear correlation between surface roughness and coating material or cutting speed.

4 Conclusion

The influence of NC coating and cryogenic heat treatment on the wear behavior and cutting performance of the carbide cutting tools in face milling of the Inconel 718 superalloy were investigated at different cutting parameters in detail. The results obtained are summarized below:

- The η phase increased by approximately 18% due to the cryogenic heat treatment in the carbide cutting tool.
- The adhesion of the hard coatings to the substrate material has been improved by the applied cryogenic heat treatment.
- The cryogenic heat-treated cutting tools coating surfaces were more homogeneous and smooth.
- After cryogenic heat treatment at cutting speed of 30 m/min, tool life of uncoated, TiN-, NC-, and TiAlN-coated carbide cutting tools increases by 54, 110, 29, and 30%, respectively, which shows that cryogenic treatment and NC coating provide a good combination for high cutting performance and tool life. The cryogenically treated NC-coated tool gives the best tool life (cutting length of 1.8 m) compared to the other tools.
- Non-treated TiN- and TiAlN-coated tools gives better tool life (1.35 m) than the NC-coated one (1.0 m) at cutting speed of 40 m/min.
- Abrasion and adhesion wear mechanisms are the main wear mechanisms for all the tools. Flank wear, notch wear, chipping, and built-up edge formation are the main tool failure modes.
- The NC coating and cryogenic heat treatment are suggested to be used in industry for longer tool life in milling of the Inconel 718.
- There is no clear correlation between surface roughness and coating material or cutting speed.

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