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ORIGINAL ARTICLE

High-speed turning of Inconel 718 by using TiAlN- and (Al, Ti) N-coated carbide tools

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Abstract
High-speed turning of Inconel 718 was challenged by using TiAlN-coated tungsten carbide tools of positive and negative types, and aluminum-rich (Al, Ti) N-coated ones of negative type. It is found that the (Al, Ti) N negative inserts have much longer tool life than the TiAlN inserts of both the positive and negative types at all the cutting speeds tested. The skirt flank wear was almost the same in mechanism, which was dominated by adhesive wear and abrasive wear for the three types of inserts at the all cutting speeds tested. The cutting edge flank wear changed greatly both in magnitude and in mechanism depending on the type of the insert and the cutting speed. The rake wear was almost limited within the cutting area and at tool life the coatings in the cutting area were all worn off except of the (Al, Ti) N negative inserts tested at the cutting speed of 200 m/min. The hardness of the turned surfaces was always higher than that as received, and the increase in the hardness was greatest for the (Al, Ti) N negative inserts among the three types of the inserts.

Keywords Inconel 718 · High-speed turning · TiAlN-coated carbide tools · (Al, Ti) N-coated carbide tools · Wear · Tool life · Surface integrity

1 Introduction

Inconel 718 alloy, a nickel-based superalloy, has a superior combination of high-temperature corrosion resistance, oxidation resistance, and creep resistance that makes it widely used in aircraft engine components, industrial gas turbine components for power generation, and petrochemical equipment. However, Inconel 718 alloy is one of the most difficult to machine materials due to its physical and mechanical properties such as low thermal conductivity, high strength at cutting temperatures, presence of hard, abrasive intermetallic compounds and carbides, and the high work hardening [1].

The advance of cutting tool materials has supported the industrial application of nickel-based alloys. Cubic boron nitride (CBN) and ceramic cutting tools are the first choice for machining Inconel 718 owing to their high hot hardness, high wear resistance, high thermal stability, and high resistance to chemical attack, but their unpredictable failure remains a main concern in choice [2]. CBN cutting tools have been tested at high cutting speeds of 350 m/min [3] and 500 m/min [4], while the concept of high-speed cutting for carbide cutting tools refers to speeds over 40 m/min [5]. Alumina (Al_2O_3) and silicon nitride (Si_3N_4) are two main ceramics used in cutting tool. Pure oxide (Al_2O_3+ZrO_2) ceramic tools are not suitable for cutting nickel-based alloys due to their low thermal shock resistance and low fracture toughness [1]. The performance of pure oxide ceramic tools is improved by adding titanium carbide (TiC) [6]. Silicon carbide (SiC) whisker-reinforced alumina tools gave lower notch wear than Al_2O_3–TiC tools, but higher flank wear, in the cutting speed range of 100–300 m/min [7]. Altin et al. [8], on the other hand, conducted comparison experiments between SiC whisker-reinforced alumina tools and sialon tools in the cutting speed range of 150–300 m/min and found that the dependences of flank wear on the cutting speed were similar between the two ceramic tools, and the optimum cutting speed was around 250 m/min for both the ceramic tools. Cutting experiments on CBN tools showed that the initial crater wear was reduced by around 40% by polishing the rake face [9].

Coating is another development in tool materials. Jindal et al. [10] showed that TiCN- and TiAlN-coated carbide tools

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performed much better than TiN-coated ones in turning of Inconel 718 at cutting speeds of 46 and 76 m/min since TiAlN has higher hardness, and higher chemical stability than TiCN or TiN over 750 °C. $(Ti_{1-x}Al_x)N$ coatings has the highest hardness at $x = 0.5$ [11] or $x = 0.6$ [12]. Prengel et al. [13] conducted Inconel 718 turning test for multilayer coated carbide tools at cutting speeds of 61 and 76 m/min, and found that the TiAlN multilayer coating has longer life than the TiAlN monolayer coating. The comparison turning experiments of Inconel 718 with TiAlN monolayer-coated carbide tools and $TiCN/Al_2O_3/TiN$ multilayer-coated ones in the cutting speed range of 50~100 m/min by Bhatt et al. [14] showed that the TiAlN monolayer-coated tools have much higher wear resistance than $TiCN/Al_2O_3/TiN$ multilayer-coated tools. However, in turning of Inconel 718 at cutting speeds of 60 and 90 m/min under minimal quantity lubrication, $TiCN/Al_2O_3/TiN$ multilayer coatings was superior to both TiN/AlN multilayer coatings and TiAlN monolayer coatings [15].

In this paper, Inconel 718 was turned in high speed by using TiAlN-coated tungsten carbide tools and aluminum-rich (Al, Ti) N-coated tungsten carbide tools, and the differences between the two different coatings in high-speed turning of Inconel 718 were clarified in terms of tool life, the wear of tools, and the quality of the turned surface.

2 Experimental method

High-speed turning of Inconel 718 alloy was carried out with coated carbide cutting tools under lubrication of water soluble cutting fluid on a Mazak CNC turning center. Inconel 718 workpieces were round bars with ϕ50 mm × 100 mm. The cutting speeds were changed among 120, 160, and 200 m/min at a feed rate of 0.08 mm/rev and a cut depth of 0.5 mm. Commercially available TiAlN-coated carbide inserts of both positive style (ISO number CCGT 09 T304-FJ) and negative style (ISO number CNGG 120404-FJ), which have the equal rake angle of 14°, and aluminum-rich (Al, Ti) N-coated carbide inserts of negative style (ISO number CNMG120404-LS), of which the rake angle is 20°, were used. The positive style inserts were set on left hand style tool holder of ISO number SCLCL1212F09 with an approach angle of 95°, whereas the two negative style inserts were set on left hand style tool holder of ISO number PCLNL2020K12 which has a seating surface with an approach angle of 95°, front and side clearance angles of 6°. The geometries of inserts after being mounted are shown in Table 1. All the inserts have the same nose radius of 0.4 mm.

The wear surfaces of tools were observed by using the FE-SEM and EDS. 3D topography images of the machined surfaces were acquired in terms of laser optical microscopy. The micro-hardness was measured by using Mitutoyo hardness testing machine under an applied load of 0.2 kgf. Thirty

Table 1 Geometries of inserts after setting

	TiAlN positive	TiAlN negative	(Al, Ti) N negative
Chip breaker	Present	Present	Present
Nose radius (mm)	0.4	0.4	0.4
Effective side rake angle (°)	9	3	14
Effective back rake angle (°)	14	8	14
Effective clearance angle (°)	7	6	6

measurements were made and then the average was determined. The tool flank wear was measured by using an optical microscope and the average flank wear value, $VB_B = 0.3$ mm, was chosen as the tool life criterion according to International Standard Organization (ISO 3685). Otherwise, the cutting would be terminated in the case of excessive chipping or fracture of the cutting edge. The experiment was conducted one time for each condition.

3 Results and discussion

3.1 Tool life and tool wear

3.1.1 Tool life

Figure 1 shows the increase of flank wear with the cutting distance at three different cutting speeds of 120, 160, and 200 m/min for (a) the TiAlN positive inserts, (b) the TiAlN negative inserts, and (c) the (Al, Ti) N negative inserts. From Fig. 1, it is known that, for all the three types of inserts, the flank wear increased with the cutting distance and there was an initial period in which the flank wear was almost independent of the cutting speed. The length of the initial period was different for different types of insert, and it increased in order of the TiAlN positive inserts, the TiAlN negative inserts, and the (Al, Ti) N negative inserts. The initial period was 80, 200, and 320 m, respectively for the TiAlN positive inserts, the TiAlN negative inserts, and the (Al, Ti) N negative inserts. After the initial period, the flank wear showed a sudden increase within a short interval at all the cutting speeds for the TiAlN positive inserts, and the TiAlN negative inserts, but the sudden increase was only observed at the highest cutting speed of 200 m/min for the (Al, Ti) N negative inserts.

The tool life both in cutting length and cutting time was summarized in Fig. 2, which was defined as the cutting length or cutting time before $VB_B = 0.3$ mm, for all the tests with the exception of the test for the TiAlN negative inserts at the cutting speed 160 m/min where the test was terminated before the tool life for the occurrence of fracture. For all the three types of inserts tested, the tool life

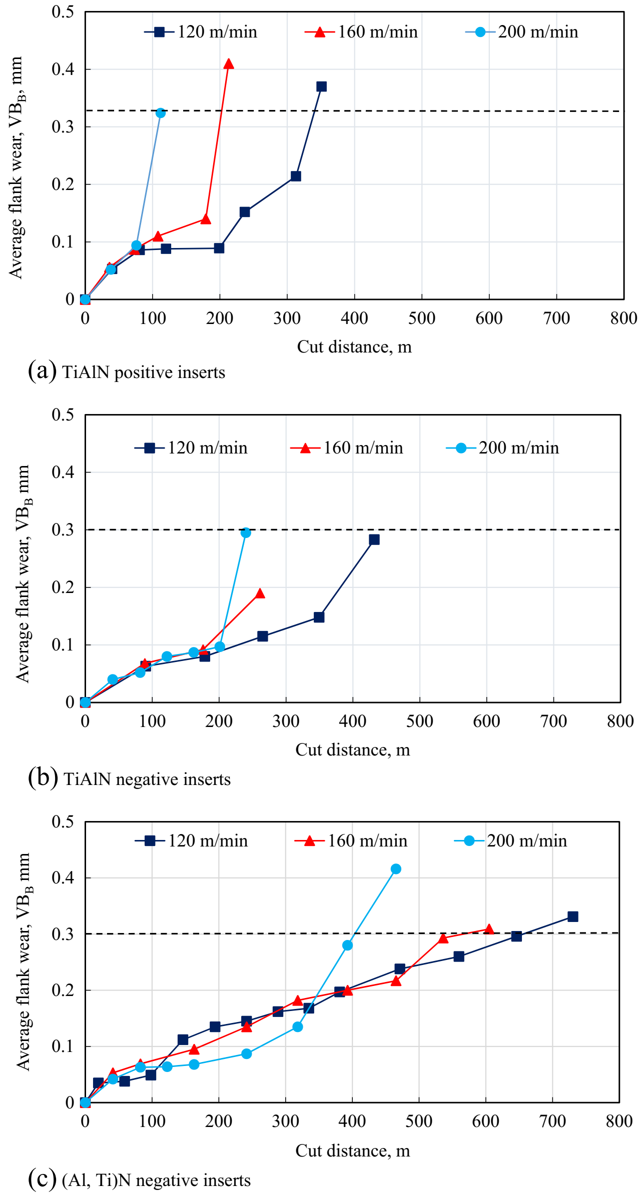


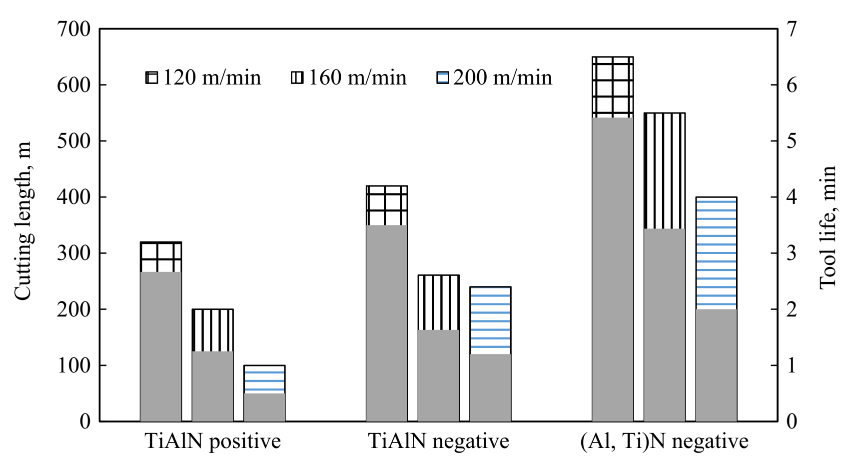
Fig. 1 Relation between cutting distance and average flank wear at different cutting speeds **a** for TiAlN positive inserts, **b** for TiAlN negative inserts, and **c** for (Al, Ti) N negative inserts

decreased as the cutting speed increased. When the cutting speed changed from 120, 160, to 200 m/min, the life reduced from 320, 200, to 100 m for the TiAlN positive inserts, from 420, 260, to 240 m for the TiAlN negative inserts, and from 650, 550, to 400 m for the (Al, Ti) N coatings, respectively. The (Al, Ti) N coatings has much longer tool life than the TiAlN coatings and higher limit cutting speed as well. On the other hand, the experimental results that the tool life of the TiAlN positive inserts was shorter than that of the TiAlN negative inserts suggested that increasing the effective side rake angle may reduce the tool life since the main difference between the two types of inserts was in the effective side rake angles, which was 9° for the former and 3° for the latter. In spite of the adverse effect of the side rake angle, the (Al, Ti) N negative inserts, of which the effective side rake angle was 14°, still gave a longer tool life than the TiAlN negative inserts.

3.1.2 Tool wear

Figure 3 is the observations of the worn flank surfaces of the TiAlN positive inserts, the TiAlN negative inserts, and the (Al, Ti) N negative inserts at different cutting speeds of 120, 160, and 200 m/min. The flank wear can be divided into the cutting edge wear and the skirt flank wear which is the wear extended down from the cutting edge. It was the same for all the observations in Fig. 3 that the skirt flank worn surfaces were smooth and the mild adhesive wear was dominant. The cutting edge wear shows very different appearances for different observations. For the TiAlN positive inserts, the built-up edge was observed at all the cutting speeds tested, but the cutting edge wear changed as the cutting speed increased. At the cutting speed 120 m/min, only adhesive wear and abrasive were observed. However at cutting speeds of 160 and 200 m/min, chipping occurred together with adhesive wear and abrasive wear, and the built-up edge was generated at the chipping areas. For the

Fig. 2 Cutting length (pattern filled bar) and tool life (gray filled bar) of the different types of inserts



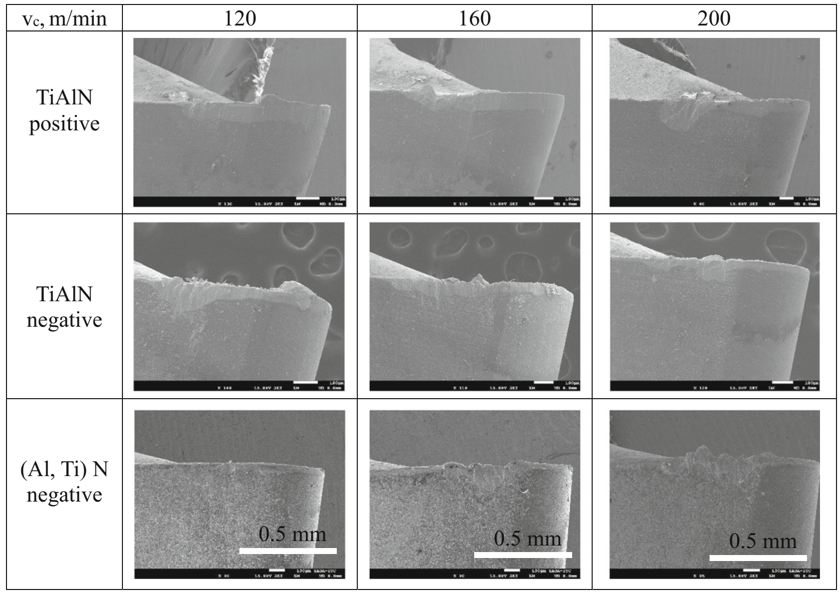


Fig. 3 Observations of flank wear for TiAlN positive inserts, TiAlN negative inserts, and (Al, Ti) N negative inserts

TiAlN negative inserts, on the contrary, both chipping and built-up edge occurred at the low cutting speed 120 m/min only, and increasing the cutting speed reduced the cutting edge wear. The (Al, Ti) N negative inserts showed the smallest cutting edge wear among the three types of inserts at the low cutting speed 120 m/min, where no chipping and no built-up edge was observed. The cutting edge wear of the (Al, Ti) negative inserts increased as the cutting speed increased, chipping occurred at the cutting speeds over 160 m/min, and the built-up edges appeared at the cutting speed 200 m/min.

The rake surface of the inserts after turning test was observed by using the FE-SEM and EDS, and the results are summarized in Fig. 4. EDS mapping was conducted for nickel of a typical composition from the workpiece, for titanium of a typical composition from the coating of the tool, and for tungsten of a typical composition from the substrate of the tool. First, from the FE-SEM images of Fig. 4, it is known that, for all the tests, the wear mainly occurred in the cutting area of the rake face, of which the width was approximately equal to the feed per revolution 0.08 mm, and among the three types of inserts, the wear increased as the cutting speed increased in spite of the cutting distance was shorter for higher cutting speed. The TiAlN positive inserts showed the severest rake wear of the cutting area at the same cutting speed. The trends of the wear observed from the FE-SEM images were reaffirmed from the Ti-Kα maps of which the dark area means the wear-off of the coating, and from the W-Mα maps of which the bright area shows the exposure of the substrate in terms of wear. For the TiAlN positive inserts, the bright areas in W-Mα maps extended much more widely than the negative inserts of both the TiAlN and the (Al, Ti) N at all the test cutting speeds. The bright area of the Ni-Kα map is an indication of the adhesive of the workpiece material onto the rake surface. For all the tests except one of the (Al, Ti) N insert at the cutting speed 200 m/min, the bright areas in the Ni-Kα map were congruent with the cutting areas, meaning that the adhesive of workpiece material occurred only in the cutting areas. For the exception of the (Al, Ti) N inserts at the cutting speed of 200 m/min, no clear bright area in the Ni-Kα map was observed. The (Al, Ti) N inserts showed smallest bright areas in both the Ni-Kα maps and the W-Mα maps among the three types of inserts tested.

3.2 Machined surface topography

3D optical observations of machined surfaces at the end of tool life are shown in Fig. 5. The cutting marks remained clear for all the tests even at the end of tool life except for the test of the TiAlN positive inserts at the cutting speed 200 m/min where the ridges of the cutting mark were squashed. The theoretical roughness is 0.51 μmRa for the nose radius 0.4 mm and the feed rate 0.08 mm/rev in this study. The fact that the real surface roughness was greater than the theoretical roughness was due to the built-up edge for the TiAlN positive inserts, and due to the chipping and the built-up edge for the TiAlN negative inserts. The (Al, Ti) N negative inserts produced surfaces with the roughness of less than the theoretical value that was attributed to the increased nose radius in terms of the wear.

3.3 Machined surface hardness

The machined surface hardness both at the beginning of the cutting and at the end of tool life for all the tests was

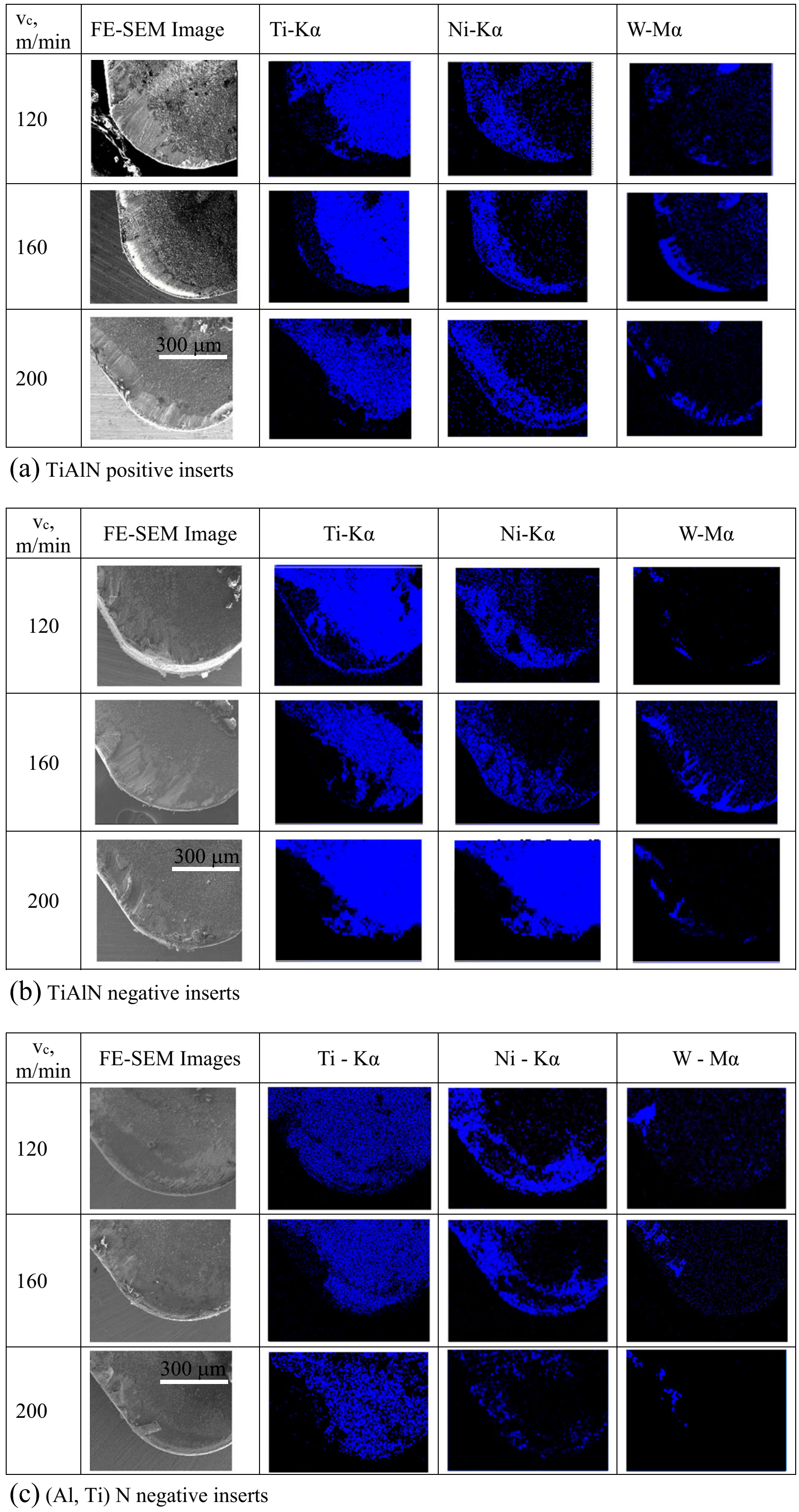


Fig. 4 EDS mapping of rake faces after turning Inconel 718: **a** for TiAlN positive inserts, **b** for TiAlN negative inserts, and **c** for (Al, Ti) N negative inserts

shown in Fig. 6. It is clear from Fig. 6 that the machined surface hardness increased as the cutting processed both for the TiAlN positive inserts and for the (Al, Ti) N negative inserts of which the effective rake angles were 9° and 14°, respectively, much higher than that of the TiAlN negative inserts. The effective side rake angle of

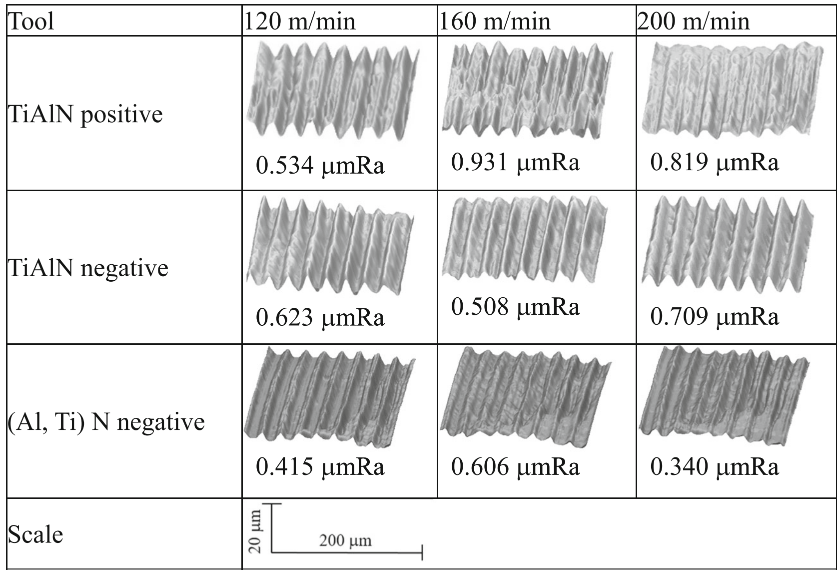


Fig. 5 3D optical observation of surfaces machined at the end of tool life

the TiAlN negative inserts was 3° and the hardness increase did not change during the cutting.

The difference in the hardness at the different cutting time is attributed to the change in the tool geometry, especially the rake angle, owing to the wear of the cutting edge. The wear decreased the rake angle, resulting in an increase in the work hardening. The hardness at the beginning increased as the rake angle of the cutting tool decreased, but the trend was reversed at the tool life. The increases in the hardness both at the beginning of cut and at the tool life were almost independent of the cutting speed for the (Al, Ti) N negative inserts, but for TiAlN inserts both of the positive type and of the negative type, the hardness tended to increase with the cutting speed. The TiAlN positive inserts at the tool life were an exception where the hardness was almost independent of the cutting speed.

4 Conclusion

The high-speed turning experiments of Inconel 718 by using the TiAlN- and the (Al, Ti) N-coated tungsten carbide tools at cutting speeds of 120, 160, and 200 m/min on the Mazak CNC turning center led to the following conclusions:

(1) The skirt flank wear was almost the same in mechanism which was dominated by adhesive wear and abrasive wear for the three types of inserts at the all cutting speeds tested.
(2) The cutting edge flank wear changed greatly both in magnitude and in mechanism depending on the type of the insert and the cutting speed.
(3) The rake wear was almost limited within the cutting area. At tool life, the coatings in the cutting area were all worn off except of the (Al, Ti) N negative inserts tested at the cutting speed 200 m/min.

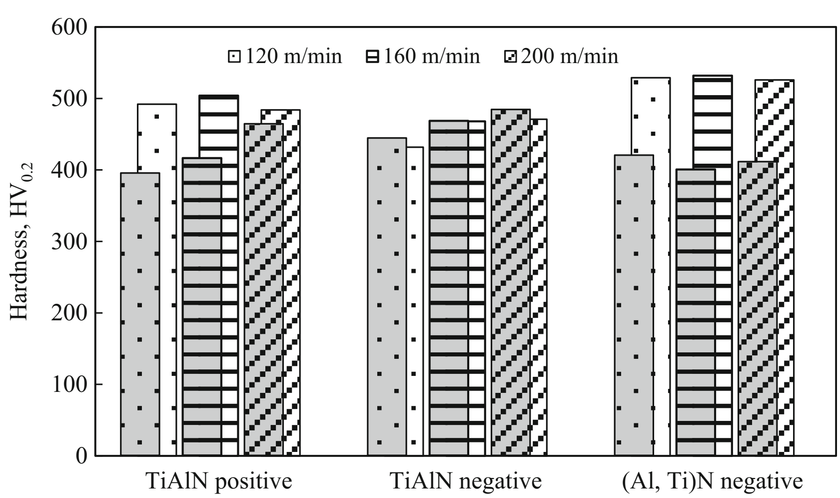


Fig. 6 Machined surface hardness at three different cutting speeds for the three types of coated cutting tools: the gray background for that at the beginning of cut and the white background for that at the end of tool life

(4) The hardness of the turned surfaces was always higher than that as received, and the increase in the hardness was the greatest for the (Al, Ti) N negative inserts among the three types of the inserts.

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