Technologia i Automatyzacja Montażu

Volume 123, Issue 1/2024, Pages 23-29
https://doi.org/10.7862/tiam.2024.1.4

Original Research

EFFECT OF TIBW ANTI-WEAR COATING ON CUTTING TOOLS FOR MILLING OF NICKEL ALLOYS ON TOOL WEAR AND INTEGRITY OF STATE OF THE TECHNOLOGICAL SURFACE LAYER

WPŁYW POWŁOKI PRZECIWZUŻYCIOWEJ TIBW NA FREZACH DO OBRÓBKI STOPÓW NIKLU NA ZUŻYCIE NARZĘDZIA ORAZ STAN TECHNOLOGICZNEJ WARSTWY WIERZCHNIEJ

Witold HABRAT[1,*], Jarosław TYMCZYSZYN[1], Anna SKROBAN[2], Nikolaos KARKALOS[3]

[1] Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, al. Powstańców Warszawy 8, 35-959 Rzeszów, Poland
[2] BRYK Sp. z o.o., 36-002 Jasionka 954H, Poland
[3] National Technical University of Athens, School of Mechanical Engineering, 15780 Zografou, Greece

* Corresponding author: witekhab@prz.edu.pl, tel.: +48 17 865 1491

Abstract

In the article, research was carried out to determine the impact of the TiBW anti-wear coating on the operational properties of cutting tools for machining nickel alloys. The dynamics of tool wear were determined on the basis of changes in the components of the total cutting force, microscopic observation of wear on the flank surface, and observation of wear based on SEM images. The condition of the technological surface layer was also determined in the form of changes in the microstructure morphology and hardening of the surface layer. The research was compared to a reference tool with the same geometry with an AlTiN coating. It was shown, among other things, that TiBW coatings can be used successfully for cutting tools for machining nickel alloys, and that the wear dynamics is similar to those of tools with the AlTiN coating. The analyses confirmed the significant thermomechanical impact of the cutter during machining, manifested by chipping and a tendency to strengthen the processed material. On the basis of observations of the microstructure of the surface layer after processing, it was shown that the thermal conductivity of the TiBW coating may be lower than that of the AlTiN coating, which is reflected in the different depths of the thermomechanical interaction zones.

Keywords: anti-wear coatings, TiBW, milling, nickel alloys, surface layer

Streszczenie

W ramach przeprowadzonych badan określono wpływ powłoki przeciwzużyciowej TiBW na właściwości eksploatacyjne narzędzi skrawających do obróbki stopów niklu. Określono przy tym dynamikę zużycia narzędzia na podstawie zmian składowych całkowitej siły skrawania, obserwacji mikroskopowej zużycia na powierzchni przyłożenia oraz obserwację zużycia n podstawie obrazów SEM. Określono również stan technologicznej warstwy wierzchniej w postaci zmian morfologii mikrostruktury oraz utwardzenia warstwy przypowierzchniowej. Badania odniesiono do narzędzia referencyjnego o tej samej geometrii z powłoką AlTiN. Wykazano m.in., że powłoki TiBW mogą być z powodzeniem stosowane na narzędzia skrawające do obróbki stopów niklu a dynamiki zużycia jest podobna do narzędzi z powłoką AlTiN. Analizy potwierdziły istotne oddziaływanie termo-mechaniczne freza podczas obróbki objawiające się wykruszeniami oraz tendencją do umocnienia materiału obrabianego. Na podstawie obserwacji mikrostruktury warstwy wierzchniej po obróbce wykazano, że przewodność cieplna powłoki TiBW może być mniejsza niż w przypadku powłoki AlTiN, co objawia się w różnej głębokości stref oddziaływań termo-mechanicznych.

Słowa kluczowe: powłoki przeciwzużyciowe, TiBW, frezowanie, stopy niklu, warstwa wierzchnia

1. Introduction

Cutting tools are fundamental elements of machining processes in order to remove material for the final desired shape of mechanical parts to be created. A wide variety of cutting tools exist, depending on the machining process and specific operation such as turning inserts, end mills, or drills. Tool wear constitutes a significant problem for cutting tools and an important component of machining cost as well. Thus, appropriate coatings are often applied to cutting tools as a means of improving their performance and extending their service life by protecting them from the influence of friction and intense heat produced during machining.

Especially, when difficult-to-cut materials such as nickel superalloys are machined, it is anticipated that tool wear can be excessive, radically shortening the tool life, unless specially designed coatings or cooling strategies are employed (Buddaraju et al., 2021; Paturi et al., 2021). Nickel-based alloys are used in many high-end applications such as in the aerospace industry as they possess properties such as high hardness, high resistance to corrosion and creep, as well as poor thermal conductivity and tendency to high strain hardening (Buddaraju et al., 2021; Parida & Maity, 2018; Paturi et al., 2021; Pedroso et al., 2023). Thus, machining of these alloys can cause high tool wear rate, with different wear mechanisms occurring such as adhesion, oxidation, abrasion, debonding and diffusion (Pedroso et al., 2023). In order to overcome the problem of high wear rate, cutting tools for machining nickel alloys should have high strength and toughness, high thermo-chemical stability and thermal shock resistance (De Bartolomeis et al., 2021). For that reason specific categories of tools are recommended, such as CBN, ceramic and carbides, with appropriate coatings (De Bartolomeis et al., 2021) or processed with suitable techniques such as chemical-mechanical polishing in order to exhibit superior performance (Tanaka et al., 2022).

As machining of superalloys is nowadays very important in industrial practice, a considerable amount of relevant works has been carried out. For example, Kosaraju, Vijay Kumar and Satish (2018) and Waghmode and Dabade (2019) investigated the impact of process parameters on machining forces and surface quality during machining of nickel-based alloys. Other researchers have focused on the determination of ways to improve the wear resistance of cutting tools or reduce wear rate during machining of nickel-based alloys. Bergs, Hardt and Schraknepper (2020) showed that the cemented carbide grade has a direct influence on tool wear behavior, with submicron or ultrafine grades being superior to conventional ones but the effect on surface quality was minimum. Guimaraes et al. (2023) performed a novel study, presenting the consequences of machining nickel alloys with a worn tool on residual stresses, corrosion, fatigue and surface hardness, clearly indicating that tool wear has a detrimental effect on the workpiece integrity.

Hadi et al. (2013) and Li, Zeng and Chen (2006) proved that milling mode also has an impact of tool wear, as down-milling should be preferred over up-milling. Moreover, the monitoring of cutting forces can be a significant indicator for tool wear. Sørby and Vagnorius (2018) noted that high pressure cooling does not affect tool wear significantly but facilitates chip breaking. Parida and Maity (2018) evaluated the performance of nickel alloy machining under elevated temperatures and observed a notable reduction of forces, roughness and tool wear. Yildirim (2019) compared various advanced cooling methods for enhancing machinability of nickel alloys and determined that the lowest tool wear was obtained by cryo-MQL strategy with nanofluids. Finally, apart from experimental work, some authors such as Parida and Maity (2019) and Lotfi, Jahanbasksh and Farid (2016) performed FE simulations to study subjects relevant to superalloy machining, such as hot machining or tool wear between different types of cutting tools.

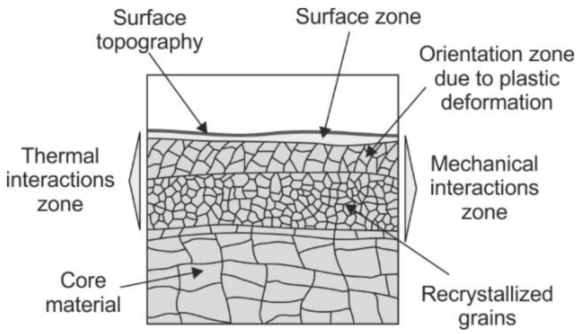

Fig. 1. Structure of the technological surface layer after cutting processes

The application of nickel alloys in aircraft technology brings additional construction requirements to the quality of the final product including the state of the technological surface layer (Fig. 1).

In the present work, an experimental work is carried out to determine the effect of a special TiBW anti-wear coating on tool wear and integrity of machined surfaces during machining of Inconel 718 alloy. For that reason, side milling experiments were carried out under specific conditions, with two different types of coating, and their performance was evaluated by observing cutting force components at different stages of tool wear, as well as by measuring flank wear and surface hardness. Finally, analysis of the results justified the superiority of the TiBW coating.

2. Material and methods

2.1. Workpiece material

The workpiece material in this study was Inconel 718, which is a high-temperature resistant nickel-based superalloy. The surface of this material exhibited a hardness of approximately 36 HRC.

The chemical composition of Inconel 718 includes several alloying elements as follows: Nickel and Cobalt (Ni+Co) content ranges from 50% to 55%, Chromium (Cr) content varies from 17% to 21%, Iron (Fe) serves as the balance component, Cobalt (Co) constitutes 1%, Molybdenum (Mo) ranges from 2.8% to 3.3%, Niobium and Tantalum (Nb+Ta) content is between 4.75% and 5.5%, Titanium (Ti) ranges from 0.65% to 1.15%, Aluminum (Al) varies from 0.20% to 0.80%, Carbon (C) content is 0.08%, Manganese (Mn) is at 0.35%, Silicon (Si) at 0.35%, Boron (B) at 0.006%, and Copper (Cu) is present at 0.3%.

Typically, the mechanical properties of Inconel 718 exhibit the following mechanical properties under ambient conditions (PN-EN ISO 6892-1:2020-05): a tensile strength of 1240 MPa, an elastic strength (0.2%) of 1036 MPa and Young's modulus of 211 GPa.

This particular nickel-chromium-based superalloy is classified as a precipitation hardening alloy, with austenite as the alloying phase that crystallises in the crystal lattice A1 and serves as the matrix material. Inconel 718 is classified as a difficult to machine material, falling into the group "S" according to ISO standards.

2.2. Cutting tools

Carbide tools for the purposes of the research were manufactured with the use of ultra-micrograin grade CKi®12 (Ihle) with extreme toughness and hardness, thus highly recommended e.g. for machining titanium alloys, heat-resistant alloys, austenitic stainless steels, hardened steels. The geometry of the milling cutter intended for the tests is shown in Fig. 2.

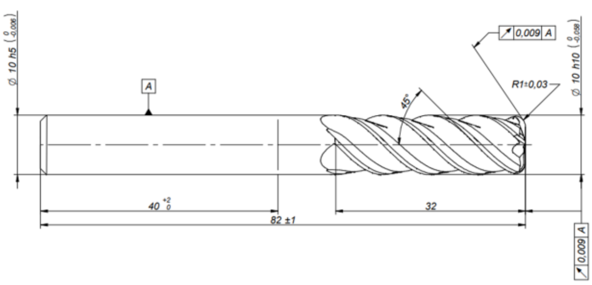

Fig. 2. The geometry of the cutting tool used for tests

The prepared tools were covered with the use of TiBW coating with a thickness of 1.3μm (Fig. 3).

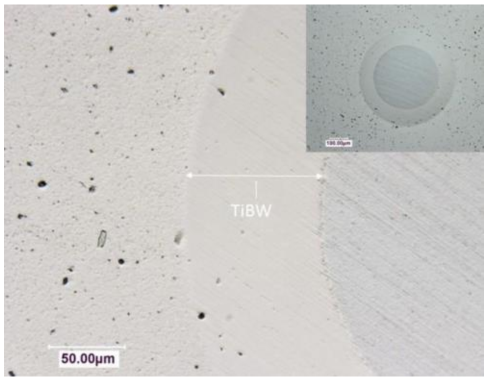

Fig. 3. TiBW coating thickness measurement – ball cratering test

In order to relate the obtained results to commercially available material solutions in terms of improving wear resistance, a reference tool with a commercially available AlTiN coating, commonly used for machining Inconel alloys, was prepared.

2.3. Cutting condition

The tests were carried out on a DMU 80 P duoBlock CNC milling machine (Fig. 4). The test stand was equipped with a Kistler piezoelectric dynamometer with a measuring range of ±5 kN attached to the machine table. The signal from the force meter is transferred to the charge amplifier and transmitted to the computer via the USB port using a 16-bit analog-to-digital converter with a measurement range of ± 10 V. The signal was visualized, processed and saved using a program developed in the LabVIEW environment. The signal sampling frequency was set to 2 kHz.

Fig. 4. Test stands built based on the DMU 80 P duoBlock CNC milling machine

The following cutting parameters were adopted:
- cutting speed v_c = 25 m/min,
- depth of cut a_p = 2 mm,
- cutting width a_e = 2.5 mm,
- feed f = 0.03 mm/tooth.

The microstructure of the surface layer was observed for samples cut from the processed material in the area for blade wear corresponding to the cutting distance L = 150 mm and L = 450 mm. The side surface was observed after the milling process (Fig. 5).

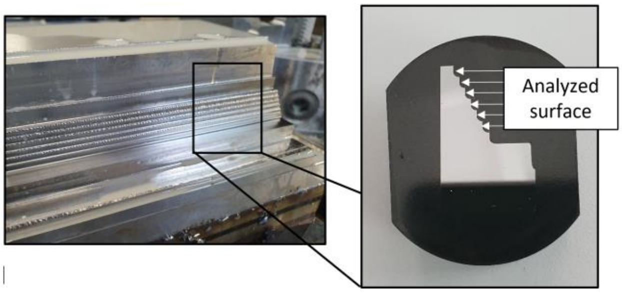

Fig. 5. The analysed side surface after processing

3. Results and discussion

The wear of the cutting tool blade results in a change in the mechanical impact conditions and, consequently, in the components of the total cutting force. Monitoring these forces allowed comparison of the operational wear of the tested and reference tools. The measured components determine the averaged maximum values for the force fluctuations resulting from the cutting of subsequent blades. The Fx component was defined in the feed direction, Fy perpendicular to the feed, and Fz in the axial direction.

The figures below show a graph of changes in the measured components of the total force as a function of the cutting length in relation to the reference tool with the AlTiN coating (Fig. 6) and the cutting tool with the TiBW coating (Fig. 7).

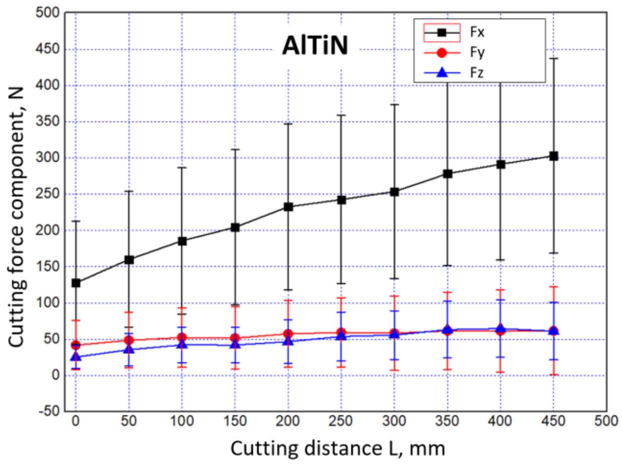

Fig. 6. Graph of changes of the total cutting force components as a result of tool wear as a function of cutting distance up to 450 mm for a cutter with an AlTiN coating

The obtained results show significant similarities in terms of the increase in force of Fx - 134% for the cutter with the AlTiN coating and 125% for the cutter with the TiBW coating. This proves the good functional properties of the tested coating in the milling of nickel superalloys.

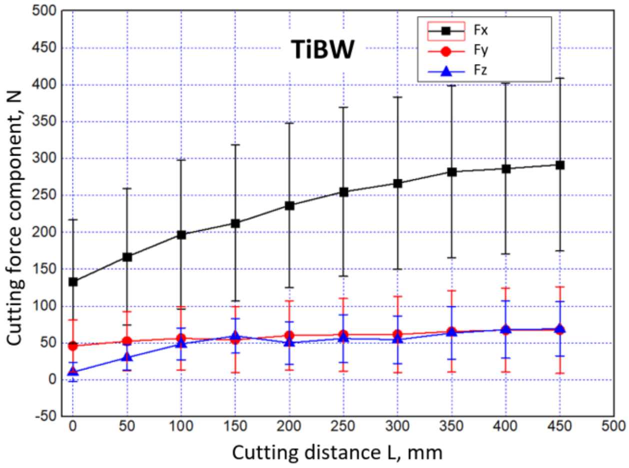

Fig. 7. Graph of changes of the total cutting force components as a result of tool wear as a function of cutting distance up to 450 mm for a cutter with a TiBW coating

The analysis of wear on the tool flank surface after cutting distance 450 mm (approximately 6 min 17 s) also did not show significant differences (Fig. 8).

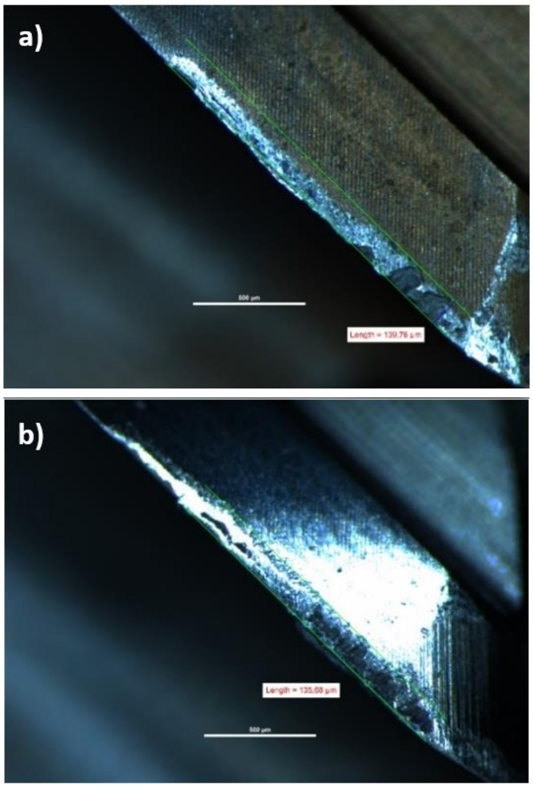

Fig. 8. Wear on the flank surface after cutting 450 mm for a tool with coating a) AlTiN, b) TiBW

Both abrasion and chipping of the blade can be observed. In the case of a tool with a TiBW coating, the chipping area appears to be slightly larger. SEM analysis of the wear of the cutting edge of the TiBW-coated tool confirmed cracks in the blade, which may be the result of thermomechanical interactions in the cutting zone (Fig. 9). This thesis is confirmed by the analysis of the microstructure of the surface after machining with a tool in the initial and final stages of wear (Fig. 10 and 11).

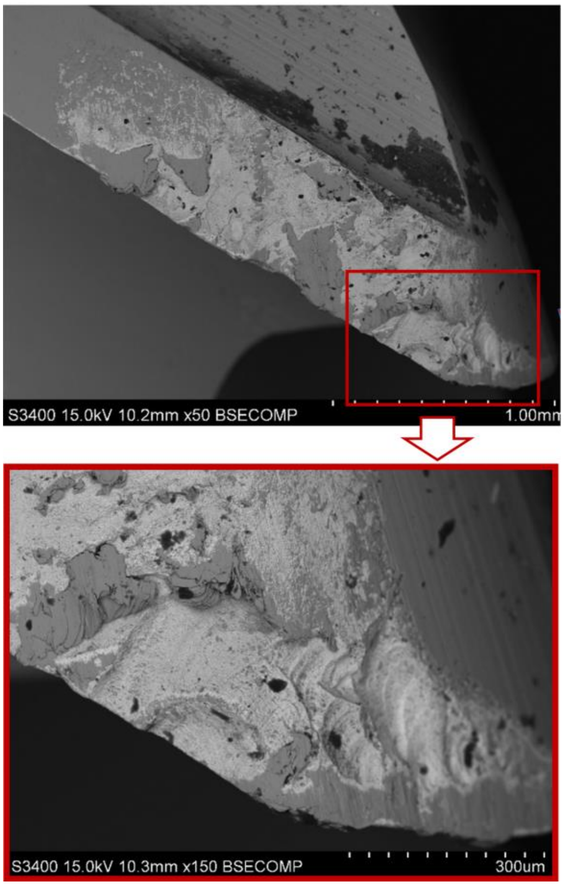

Fig. 9. SEM image of the wear of the cutting edge of a tool with a TiBW coating

In the case of a tool with a TiBW coating, wear significantly increases the thermomechanical influence zone, which can be observed in the form of a longitudinal texture near the machined surface to a depth not exceeding 10 mm (Fig. 10b). This effect was confirmed by the strengthening in the near-surface layer shown in Figure 12. The tendency to be strengthened by large plastic deformations for materials of the HRSA group occurs especially in the case of worn tools. An increase in cutting force due to wear and the influence of heat generated during cutting can cause this type of phenomenon.

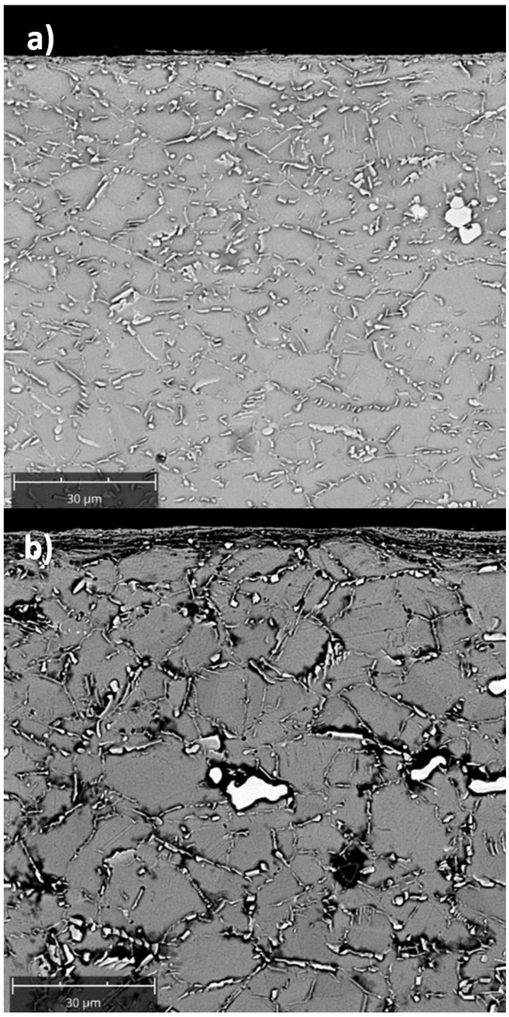

Fig. 10. Comparison of changes in the morphology of the microstructure of the surface layer after machining with a milling cutter with a TiBW coating after cutting: a) 150 mm, b) 450 mm

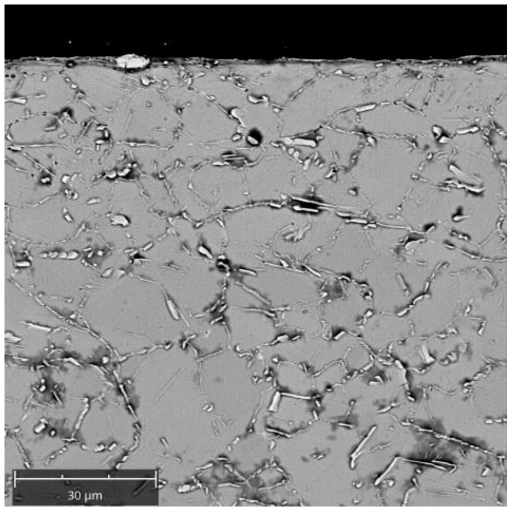

Fig. 11. Comparison of changes in the morphology of the microstructure of the surface layer after machining with a cutter with an AlTiN coating after cutting 450 mm

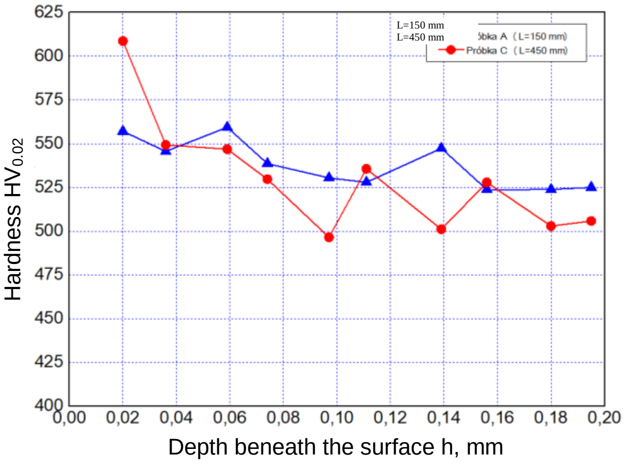

Fig. 12. Hardness distribution in the surface layer after machining with tools in various phases of wear (cutting distance L)

Comparison of changes in the morphology of the microstructure of the surface layer after processing with a worn cutter with a TiBW coating (Fig. 10b) and a cutter with an AlTiN coating (Fig. 11) allow the conclusion that the tested coatings differ from each other in terms of thermal conductivity. The potentially lower thermal conductivity of the TiBW coating causes the heat flow generated in the cutting process to be directed towards the processed material. As a consequence, this creates the above-mentioned zone of influence of thermo-mechanical interactions. However, confirmation of this thesis requires laboratory determination of thermal conductivity coefficients for the analysed coatings.

4. Conclusions

Based on the obtained results, the following conclusions were drawn:

- it was demonstrated that TiBW coatings can be successfully used for cutting tools for machining the Inconel 718 alloy, showing similarity in wear dynamics to commonly used tools with commercially available AlTiN coatings,
- determining the dynamics of wear based on changes in the components of the total cutting force showed that the component in the feed direction is the largest, and its increase over the assumed period of operation (approximately 6 min of cutting) was - 134% for the cutter with an AlTiN coating and 125% for the cutter with the coating TiBW,
- the amount of wear on the flank surface for the analyzed tools did not show significant differences, while for the tool with the TiBW coating a slightly larger area of chipping could be observed,
- SEM analysis of the worn blade and a graph of hardness as a function of depth from the surface confirmed the significant thermo-mechanical impact of the cutter during processing, manifested by chipping and a tendency to strengthen,
- based on observations of the microstructure of the surface layer after processing, it was shown that the thermal conductivity of the TiBW coating may be lower than that of the AlTiN coating. This directs the heat flow generated in the cutting process towards the workpiece material and translates into the depth of deformation. Confirmation of this, however, requires further material and operational tests.

Acknowledgments

Research financed by the project "New cutting tools with innovative anti-wear coatings for machining nickel-based superalloys used in aviation technology" RPPK.01.02.00-18-0020/19 implemented at P.P.U.H. "BRYK" Witold Bryk, 36-002 Jasionka, Jasionka 954

References

Bergs, T., Hardt, M., & Schraknepper, D. (2020). Investigations on the Influence of the Cemented Carbide Grade on the Surface Integrity when End Milling DA 718. *Procedia CIRP*, *93*, 1490–1495. https://doi.org/10.1016/J.PROCIR.2020.03.068.

Buddaraju, K. M., Ravi Kiran Sastry, G., & Kosaraju, S. (2021). A review on turning of Inconel alloys. *Materials Today: Proceedings*, *44*, 2645–2652. https://doi.org/10.1016/J.MATPR.2020.12.673.

De Bartolomeis, A., Newman, S. T., Jawahir, I. S., Biermann, D., & Shokrani, A. (2021). Future research directions in the machining of Inconel 718. In *Journal of Materials Processing Technology* (Vol. 297). Elsevier Ltd. https://doi.org/10.1016/j.jmatprotec.2021.117260.

Guimaraes, M. C. R., Fogagnolo, J. B., Paiva, J. M., Veldhuis, S., & Diniz, A. E. (2023). The impact of the cutting parameters and tool condition on surface integrity when milling Inconel 625. *Journal of Materials Research and Technology*, *25*, 1944–1958. https://doi.org/10.1016/j.jmrt.2023.06.071.

Hadi, M. A., Ghani, J. A., Che Haron, C. H., & Kasim, M. S. (2013). Comparison between up-milling and down-milling operations on tool wear in milling Inconel 718. *Procedia Engineering*, *68*, 647–653. https://doi.org/10.1016/j.proeng.2013.12.234.

Kosaraju, S., Vijay Kumar, M., & Sateesh, N. (2018). Optimization of Machining Parameter in Turning Inconel 625. *Materials Today: Proceedings*, *5*(2), 5343–5348. https://doi.org/10.1016/j.matpr.2017.12.119.

Li, H. Z., Zeng, H., & Chen, X. Q. (2006). An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts. *Journal of Materials Processing Technology*, *180*(1–3), 296–304. https://doi.org/10.1016/j.jmatprotec.2006.07.009.

Lotfi, M., Jahanbakhsh, M., & Akhavan Farid, A. (2016). Wear estimation of ceramic and coated carbide tools in turning of Inconel 625: 3D FE analysis. *Tribology International*, *99*, 107–116. https://doi.org/10.1016/j.triboint.2016.03.008.

Parida, A. K., & Maity, K. (2018). Comparison the machinability of Inconel 718, Inconel 625 and Monel 400 in hot turning operation. *Engineering Science and Technology, an International Journal*, *21*(3), 364–370. https://doi.org/10.1016/j.jestch.2018.03.018.

Parida, A. K., & Maity, K. (2019). FEM analysis and experimental investigation of force and chip formation on hot turning of Inconel 625. *Defence Technology*, *15*(6), 853–860. https://doi.org/10.1016/j.dt.2019.04.012.

Paturi, U. M. R., B., V. D., & Reddy, N. S. (2021). Progress of machinability on the machining of Inconel 718: A comprehensive review on the perception of cleaner machining. *Cleaner Engineering and Technology*, *5*, 100323. https://doi.org/10.1016/J.CLET.2021.100323.

Pedroso, A. F. V., Sousa, V. F. C., Sebbe, N. P. V., Silva, F. J. G., Campilho, R. D. S. G., Sales-Contini, R. C. M., & Jesus, A. M. P. (2023). A Comprehensive Review on the Conventional and Non-Conventional Machining and Tool-Wear Mechanisms of INCONEL®. In *Metals* (Vol. 13, Issue 3). MDPI. https://doi.org/10.3390/met13030585.

Sørby, K., & Vagnorius, Z. (2018). High-pressure cooling in turning of inconel 625 with ceramic cutting tools. *Procedia CIRP*, *77*, 74–77. https://doi.org/10.1016/j.procir.2018.08.221.

Tanaka, Y., Sato, H., & Eryu, O. (2022). Improved cemented carbide tool edge formed by solid phase chemical–mechanical polishing. *Journal of Materials Research and Technology*, *20*, 606–615. https://doi.org/10.1016/J.JMRT.2022.07.077.

Waghmode, S. P., & Dabade, U. A. (2019). Optimization of process parameters during turning of Inconel 625. *Materials Today: Proceedings*, *19*, 823–826. https://doi.org/10.1016/j.matpr.2019.08.138.

Yıldırım, Ç. V. (2019). Experimental comparison of the performance of nanofluids, cryogenic and hybrid cooling in turning of Inconel 625. *Tribology International*, *137*, 366–378. https://doi.org/10.1016/J.TRIBOINT.2019.05.014.