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WEAR STUDY ON THE APPLICATION OF DIPS COOLING FOR MACHINING INCONEL 718 WITH CERAMIC INSERTS

Grzegorz Dyrbuś[1]

[1]Silesian University of Technology, Faculty of Mechanical Engineering, Department of Machine Technology, Konarskiego 18a, 44-100 Gliwice, Poland

Corresponding author: Grzegorz Dyrbuś, grzegorz.dyrbus@polsl.pl

Abstract: Traditional methods of machining Inconel 718 alloys using conventional cooling cause a significant decrease in tool life, so the research attempted to determine how the use of cryogenic cooling will affect the machining. The article contains the results of experimental research, the main goal of which was to determine the possibility of using DIPS dry ice cooling for machining difficult-to-machine materials. The research involved comparing of the tool life for three types of cooling system: conventional cooling with oil emulsion, cryogenic cooling with CO2 using - Dry Ice Powder System (DIPS) and CCA (Cooled Compressed Air). Inconel 718 alloy was used as the machined material. The research methodology consisted in determining tool wear curves and determining tool life for various cooling methods. Tool wear symptoms and types of chips that appeared during machining with the tested tool inserts were also compared. The tools used for the tests were SiALON KYS30 cutting inserts from Kennametal and ceramic SEC-W Whisker-reinforced cutting inserts from Genicore. The tests were carried out for rough turning. The results showed a decrease of tool life for DIPS cooling compared to oil emulsion cooling, during Inconel 718 rought turning, therefore the tests should be extented for another group of processed materials. e.g., for hardened steels, or for another cases of machining e.g. finishing turning.
Key words: Inconel machining, DIPS cooling, ceramic insert, tool life

1. INTRODUCTION

Hard-to-machine alloys (e.g. Ti, Ni, Al) or hardened steels are increasingly used in various industries. The machining of such materials often poses a major technical challenge. Traditional machining methods using conventional cooling result in a significant decrease in tool life. The high cutting temperature of such alloys necessitates very intensive cooling of the cutting zone and the use of appropriate protective coatings. However, it should be noted that even intensive high-pressure liquid cooling cannot prevent rapid tool wear. The above enforces the need to develop new solutions for efficient machining of hard-to-machine alloys. We are talking about cryogenic methods, i.e. methods of supplying medium with temperatures below 150°C (123 K), the media used are liquid nitrogen (LN2), helium (LHe), or cooled carbon dioxide (LCO2) with temperatures approx. -50÷-78°, this means in practice that cryogenic processing starts below 0 °C [1]. However, these methods are very expensive and dangerous, both for the machine tool and the operator. An alternative seems to be the use of the Dry Ice Powder System (DIPS) cooling method that produces a cooling medium, dry ice, that is solidified carbon dioxide (sublimation point: 194.5 K = -78.5°C). This is a new cooling system belonging to cryogenic systems, but much safer due to the higher sublimation temperature, which is not implemented on an industrial scale to date, so extensive research is required to confirm the suitability of this system and to determine the group of materials for which it will be used. As a preliminary step, tests have been carried out for the processing of materials from the INCONEL group, using ceramic tools.

1.1. Cryogenic machining

Cryogenic machining is characterized by low cutting temperature this translates into very good cooling (but no lubricating medium), longer tool life and higher technological parameters (Vc, f, ap). The low temperature promotes higher strength of the workpiece material, at the same time, the tool life increases, which is why I use mainly in high-energy processes for hard-to-cut materials such as nickel alloys, titanium. There are many studies on machining of the nickel alloys [2-6], but they describe tests using LN2, LCO2 and also hybrid methods of cooling during machining of various types of tools for hard-to-machine materials including INCONEL alloys, but nowhere is DIPS dry ice cooling described. Low temperature has a positive effect on the chip morphology and functionality of the machined surface. It was also found to obtain better roughness of the machined surface for the above-mentioned alloys [7]. Undoubtedly, the advantage is the lack of disposal of coolant (gas), which is the basis of the so-called "clean production" unfortunately, it is also associated with the lack of recovery of gas, high costs of storage, transport or manufacture and specialized tools and machinery. In addition, there are problems related to worker safety (risk of frostbite), dimensional accuracy of the final component also remains problematic [1]. In turn, the use of large quantities of coolants and stringent environmental requirements have pushed the industry into waste minimization, thus creating new methods of processing with minimal coolant such as MQL (Minimal Quanity Lubiraction), CCA (Cooled Compressed Air) and others. The most developing cooling method today is cryogenics due to the cleanest process associated with the lack of cryogenic gas disposal. The most common gases in cryogenic processing are liquid nitrogen (LN2) and liquid carbon dioxide (LCO2). Both gases are colorless and odorless and have different boiling and melting points of -78.5°C and -56.6°C [8] for LCO2, while LN2 has boiling points of -196°C and -210°C [8]. Carbon dioxide will turn into so-called "dry ice" when first exiting the nozzle upon expansion, in the case of Nitrogen this phenomenon does not occur, but in both cases the white "frost" on the tools is a natural phenomenon.

1.2. Tool life in cryogenics

A number of works have confirmed the increase in tool life in cryogenic machining. For AISI 304 stainless steel and the use of indirect cooling, tool life increased almost 4 times [9]. In a study [10], a hybrid method (a combination of cryogenics and plasma heating) was used for Inconel 718 material and achieved as much as 156% higher tool life, compared to conventional methods. There are also studies describing crater formation with cryogenic jet cooling in the machining of titanium alloys. A reduction in maximum crater wear after 5 min machining was observed 33% for 70 m/min, 20% for 85 m/min and 77% for 100 m/min with cryogenic cooling compared to dry machining [11].

2. MATERIALS AND METHODS

2.1. Research plan

The research was conducted in cooperation with High Technology Machines, the research is part of a project financed by NCBiR. The purpose of the research was to determine the feasibility of using DIPS cryogenic cooling for machining Inconel alloys. The research plan was to determine the durability of 2 types of ceramic tools for three types of cooling when turning Inconel 718, and to determine the form of tool wear. The test parts were discs made of the material under study. These were low-precision parts, so the tests were conducted during rough machining.

The study was conducted for three types, cooling, continuous flooding with oil emulsion, cryogenic DIPS using CO2 dry ice and with compressed cold air CCA.

The applied DIPS cooling system using dry ice, a system that produces ice crystals from liquid CO2. The use of the DIPS system seems to be justified by economic considerations, including the availability of the active agent for this type of system. The use of CO2 will undoubtedly contribute to lower manufacturing costs compared to, one aspect may be the lack of need to clean and wash the component, which is necessary after cooling with oil emulsion. Also, the cost of purchasing agents differs significantly in favor of liquid carbon dioxide, where the cost of purchasing LCO2, is much lower compared to LN2.

The research plan was to determine the suitability of selected ceramic grades for machining the selected material and to select the better one among the chosen ones too. In addition, it was to determine the suitability of the DIPS system for the designated machining task.

During the tests, tool wear was measured. Based on preliminary tests, it was found that the most intense wear was in the form of notch wear on the cutting edge and VB flank wear. Based on literature data and previous tests, the criterion value of the wear indicator on the flank was VB = 0.6 mm.

It was assumed that each cutting test was repeated at least 3 times, in order to eliminate coarse errors, as well as to conduct tests in such a way that there were at least 5 measurements of wear magnitude on each wear curve.

2.2. Technical devices used for testing

Test stand for cutting tests

Tool life tests were conducted on an OKUMA VTM-65 (Okuma Co., Oguci, Japan) machine tool on which a Dry Ice Powder Cooling System DIPS10-1SA cryogenic cooling system was implemented. The machine tool has a 30 kW spindle, and is a three-axis vertical lathe that combines the advantages of a vertical lathe with the benefits of machining centers.

The DIPS10-1SA (DIPD HC Co., LTD., Yokohama, Japan) system is a device that uses liquefied carbon dioxide and compressed air, the high-pressure liquefied carbon dioxide is used for free expansion to produce powdered dry ice. The powdered dry ice is accelerated by the booster air and blown into the cutting zone. The dry ice displaces air, reducing oxygen concentration and creating a carbon dioxide atmosphere in the cutting area. The chemically neutral atmosphere and temperature of dry ice limit the temperature rise in the cutting zone and reduce the effect of heat on the tool, etc., which is expected to extend tool life. Injection of heated booster air along with dry ice prevents dew condensation in the nozzle, reducing the temperature drop of the tool, workpiece, equipment table, etc. by dry ice. The structure of the DIPS system is shown in Fig.1 [12].

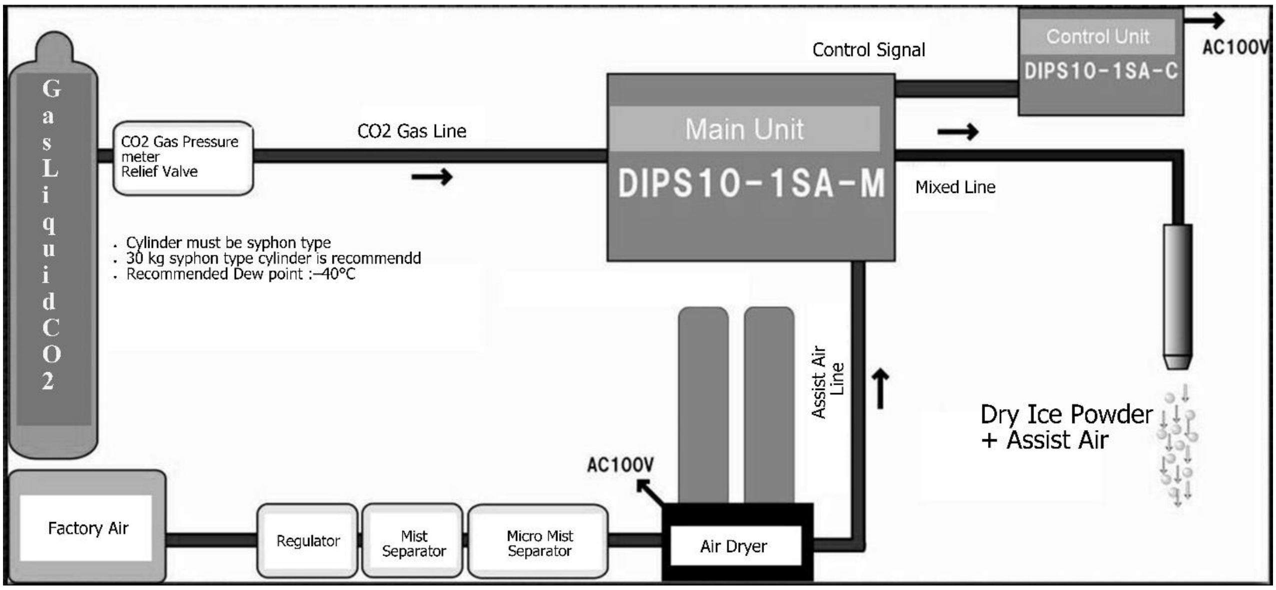

Fig. 1. Structure of the Dry Ice Powder Cooling System DIPS10-1SA [12]

Device specifications:
-Flow rate of liquefied carbon dioxide - Approximately 0.1 kg/min.
-Pressure of liquefied carbon dioxide (Mpa) - 6 (regular use).
-Booster air pressure (Mpa) - 0.5 (regular use).
-Booster air dew point (C) - Dew point at atmospheric pressure: -40 C or less (recommended).
-Control method - Liquefied carbon dioxide solenoid valve: ON/OFF control (normal closing).
-Booster air solenoid valve: ON/OFF control (normal closing).
-Power supply Single-phase, 200 V, 50/60 Hz.
-Power consumption 1.2 kW.
-Dimensions Main unit: 149W x 200D x 430H, Control unit: 330W x 149D x 200H.
-Weight Main unit: 6.5 kg, Control unit: 4.5 kg.
This device allows air alone to be blown into the cutting zone, so the DIPS device was also used during dry cutting tests. A nominal capacity of cooling air was used as in the manufacture of dry ice.
The coolant was supplied from the side of the insert to the flank and face surfaces as shown in Fig. 2.

Stand for measuring tool wear
Measurements of tool wear were performed on a Keyence VHX-7000 digital microscope (Keyence Co., Osaka, Japan). The microscope was equipped with a zoom optical lens with a magnification of 20-200x. The microscope allows observation and recording of images in 4k resolution. It allows measurements with an accuracy of 0.1 um.

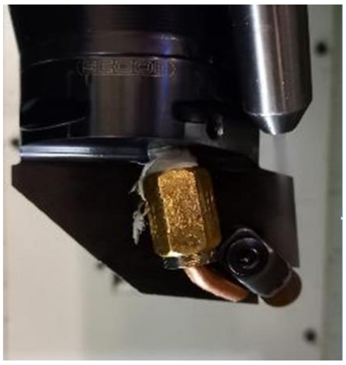

Fig. 2. Direction of coolant supply

2.3. Properties of the workpiece material

Inconel 718 alloy was chosen for the study; it is a heat-resistant nickel superalloy. Nickel superalloys are used in the most thermally stressed parts of jet engines, accounting for nearly 50% of its weight. Nickel matrix alloys are considered difficult to machine. This is evidenced, among other things, by the machinability rating (MR) index value for the entire group of superalloys taking values below 25%, with the reference material SAE 1020 steel (equivalent to DIN 1.0402) having an MR=100%. Inconel 718 alloy is particularly low rated at MR=14% [13]. The properties of the material are shown in Table 1. The material with a hardness of 35 HRc was tested. Semi-finished products in the form of a D300/d100xL40 mm ring were used for testing.

Table 1. The properties of the tested material, [14]

ANALISI DI PRODOTTO /CHEMICAL ANALYSIS									
C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Cu**	**Sn**
< 0.045	< 0.35	< 0.35	< 0.010	< 0.0100	17.00-21.00	50.00-55.00	2.80-3.30	< 0.230	
0.016	**0.21**	**0.21**	**0.007**	**0.0010**	**17.74**	**51.21**	**2.98**	**0.108**	
Ca	**Al.**	**V**	**Ti**	**W**	**Ta**	**As**	**Co**	**Nb**	**B**
< 0.0030	0.400-0.600		0.800-1.150		< 0.0500		< 1.000	4.870-5.200	< 0.0060
0.0001	**0.520**		**0.899**		**0.0208**		**0.032**	**5.062**	**0.0030**
Pb [ppm]	**Bi [ppm]**	**Mg [ppm]**	**Se [ppm]**	**Fe**	**Nb+Ta**	**Grain Size° ASTM E112**	**Ext.**	**1/2radius**	**Center**
< 5	< 0.3	< 60	< 3	INFO	4.870-5.200		> 2	> 2	> 2
< 1	**< 0.3**	**< 0.3**	**< 1**	**20.70**	**5.083**		**4**	**4**	**4**
RISULTATI PROVE MECCANICHE/ TEST RESULTS ON ACTUAL BAR PROLONGATION									
Temp. [°C]	**Direzione Direction**	**Rp_{02} [MPa]**	**Rp_1 [MPa]**	**Rm [MPa]**	**A [%]**	**Z [%]**		**KV (10 X 10 mm) [J]**	
		827-1000		**>1034**	**> 20**	**> 25**			
RT	**ASTM/T**	954		1230	22.0	28.3			
			>0.38 mm			INFO		37 min /41 avg	
- 60	**ASTM/T**	**Lateral Expansion:** 0.85-0.78-0.75 [mm] **Shear Fracture: 10-30-20**						77.6-74.9-72.4	
	Position	**HRc**	**Average**	**Position**	**HRc**	**Average**	**Position**	**HRc**	**Average**
		32-40						32-40	
RT	**Ext.**	36-37-36	**36**	**1/2r**	36-35-35	**35**	**Center**	34-35-35	**35**

2.4. Cutting tool characteristics

Due to the need to compare the results with the technological process and parameters used in the industry to date, as well as the need to compare tool performance and tool life, a ceramic tool material was selected. Of those available, new grades were selected for machining superalloys, KYS30 from Kennametal and SEC-W from Genicore.

Due to the machine tool chosen for the study, a circular insert cutter for turning/boring was used: C6-CRSNR-45065-12C equipped with the RNGN120700E KYS30 insert and SEC-W insert.

KYS30™ is the latest in a line of general-purpose α/βSiAlON grades for heat-resistant alloys machining. This grade provides excellent wear resistance, better ductility and thermal shock resistance than whisker ceramics. KYS30 also provides better thermal stability, [15].

SEC-W is a Whisker-reinforced ceramic material. It is a new tool material designed for extreme conditions (loads, temperatures, etc.). The material created with U-FAST technology, based on aluminum oxide (Al_2O_3) with the main addition in the form of SiC whiskers. Aluminum oxide ceramics are characterized by high hardness, resistance to chemical wear and compressive strength at cutting temperatures above 1000°C. Reinforcements of this type in the composite are designed to increase its bending and fracture toughness. It is suitable for machining very hard and chemically hard-to-machine materials [16].

Cutting parameters

During the cutting tests, rough turning of the face of a semi-finished product in the form of a ring with dimensions d300/d100/40 mm was carried out. Tool wear was measured after each pass. The machining was carried out with parameters as for roughing recommended by tool manufacturers. Cutting parameters such as cutting speed - Vc = 220 m/min, feed rate f = 0.12 mm/rev, depth of cut ap = 1 mm were assumed.

2.5. Cooling lubricants

The study was conducted for three cooling methods, continuous oil emulsion, cryogenic DIPS using CO2 dry ice and with compressed cooled air CCA.

During oil emulsion cooling, a 10% HOCUT® 4940 oil solution was used; this is an advanced, boron- and formaldehyde-free, highly lubricating emulsion that provides extremely long coolant life. The special additive package enables it to achieve particularly high machining performance compared to conventional products and is particularly effective for machining difficult-to-machine materials used in the aerospace industry, such as aluminum, nickel alloys and titanium. HOCUT® 4940 is recommended for difficult machining of a wide range of materials used in the aerospace industry including aluminum alloys, highly alloyed steels and hard-to-machine aerospace materials like titanium and nickel alloys [17].

During dry ice cooling (DIPS), liquid carbon dioxide LCO2 stored in special cylinders equipped with a hollow tube was used as the coolant, allowing LCO2 to be drawn from the cylinders in the liquid phase and delivered in this form to the dry ice unit.

The unit allows clean air to be fed into the cutting zone, so the DIPS unit was also used during cooling tests. This allowed the same dosing capacity to be maintained and the effect of dry ice alone on durability to be determined, without changing the capacity or direction of the coolant feed.

3. RESULTS AND DISCUSSIONS

On the basis of cutting tests, tool wear graphs were drawn up, the tool life was determined for the wear criterion index VB, the maximum wear value of 0.6 mm was assumed.

Tool wear curves for KYS30 sialon inserts for turning with different cooling methods are shown in Fig. 3-5.

The tests for cutting with air cooling were repeated several times, but the wear after one pass significantly exceeded the criterion value and were not included in the chart. Therefore, due to the very low tool life achieved for machining with air cooling, further research in this direction was abandoned.

Wear curves for Genicore SEC-W sialon inserts for machining with various cooling methods are shown in Fig. 6 and Fig. 7. Due to the much lower durability of SEC-W inserts compared to KYS30, which proves the lower suitability of this type of tools for the intended purposes, the tests were repeated only 2 cats. Also for this reason and due to the cost of the material, tests for air cooling were omitted.

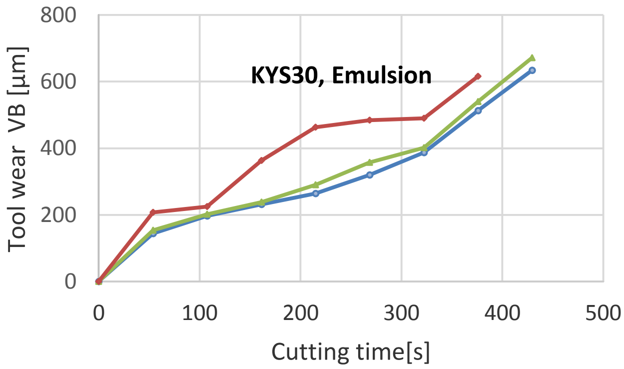

Fig. 3. KYS30 inserts tool wear curve during machining with emulsion cooling for V_c=220m/min, f=0.12mm/rev, ap=1mm

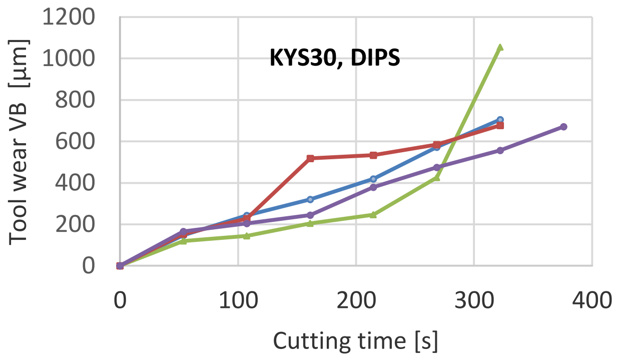

Fig. 4. KYS30 inserts tool wear curve during machining with DIPS cooling for V_c=220m/min, f=0.12mm/rev, ap=1mm

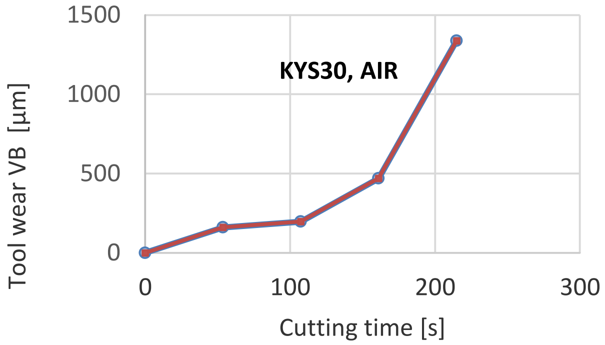

Fig. 5. KYS30 inserts tool wear curve during machining with air cooling for V_c=220m/min, f=0.12mm/rev, ap=1mm

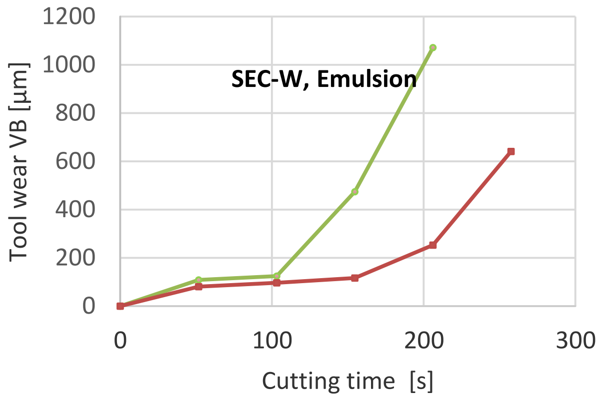

Fig. 6. SEC-W inserts tool wear curve during machining with emulsion cooling for V_c=220m/min, f=0.12mm/rev, ap=1mm

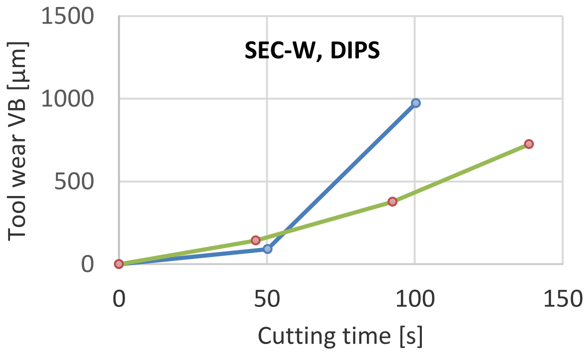

Fig. 7. SEC-W tool wear curve during machining with DIPS cooling for V_c=220m/min, f=0.12mm/rev, ap=1mm

Based on wear charts, the tool life was determined for individual cooling methods. The results of average tool life for individual types of cooling during machining are presented in Fig. 8, while the types of tool wear are shown in Fig. 9 and 10.

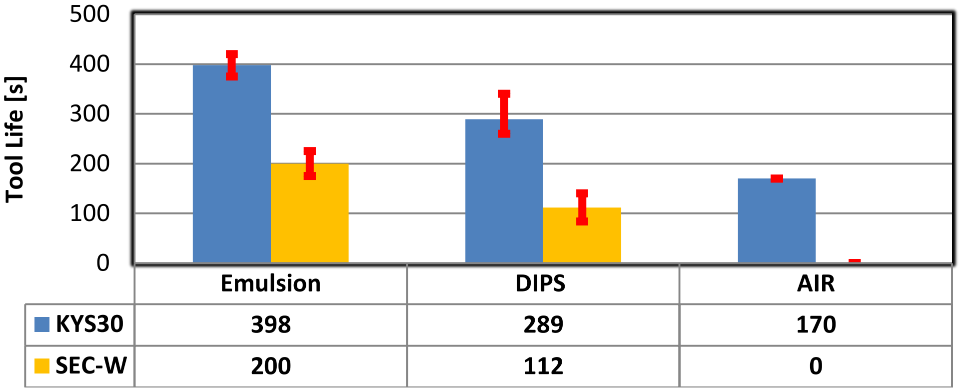

Fig. 8. Average tool life and deviation of KYS30 and SEC-W inserts, V_c = 220 m/min, f = 0.12 mm/rev, a_p = 1 mm

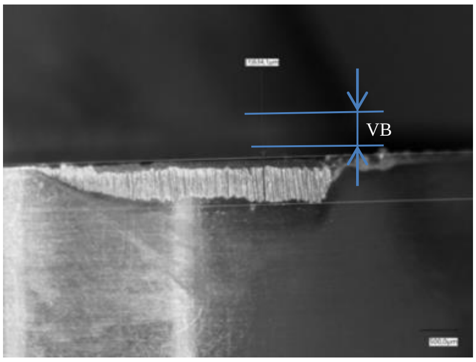

Fig. 9. Wear form of KYS30 inserts

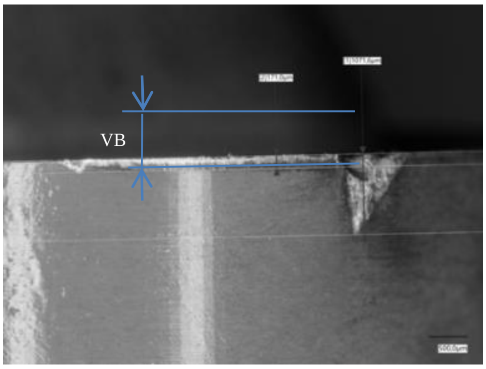

Fig. 10. Wear form of SEC-W inserts

Tool life tests for both sialon and whisker ceramics have shown that better results than the DIPS method are obtained when cooling with an oil emulsion. The reason seems to be that the cooling effect on the tool and workpiece is too weak when using dry ice cooling. Unfortunately, the DIPS system is equipped with a single nozzle and it is possible that the use of only one coolant feed nozzle is insufficient. During testing, a significantly higher workpiece temperature was observed after machining compared to emulsion cooling. Similarly, a strong heating of the workpiece was observed during air cooling. Also, the form of the chips from broken obtained during emulsion cooling changed to continuous clumped during DIPS and air cooling. The form of tool wear that was obtained during roughing with KYS30 inserts for both emulsion and DIPS cooling was satisfactory. In the main, it was a uniform abrasion on the contact surface (Fig. 9). Only when cutting with air cooling did intensive wear in the form of notching occur, which significantly reduced the tool life for this cooling method. The SEC-W ceramic tools, on the other hand, showed a strong tendency to notch at the cutting edge (Fig. 10), which resulted in the low tool life obtained with these inserts. In this case, it is likely that the introduction of a cutting strategy with a variable depth of cut into the machining process would have resulted in a more uniform distribution of wear along the edge and higher tool life.
Due to the lower cooling effect, it is likely that the DIPS system will perform well when machining less demanding materials, such as hardened steels. On the other hand, despite lower tool life, for KYS30 inserts, they are only slightly lower (approx. 27%). It should be emphasised, however, that the DIPS system is a much more environmentally friendly system by virtue of the fact that it reuses an environmentally harmful gas, and may also be cheaper to operate by not having to clean workpieces, chips or dispose of coolant.

4. CONCLUSIONS

Based on the research, the following conclusions can be drawn as follows: Tool life tests have shown that the use of DIPS dry ice cooling system during roughing reduces the tool life of SiALOn-ceramics (KYS30 inserts) by 27% compared to oil emulsion cooling. The use of Whisker ceramics (SEC-W inserts) for roughing results in a reduction in tool life of about 50% with oil emulsion cooling and 62% with DIPS cooling. Performing tests with varying depth of cut during the tool transition for SEC-W inserts can contribute to higher tool life by minimising the effect of notch wear, by spreading the adverse effect of workpiece surface along the cutting edge. Research should be extended to other grades of workpiece materials to confirm the application of the cryogenic DIPS system to the machining of other hard-to-machine materials. The use of the DIPS dry ice cooling system avoided the need to clean and wash the workpiece after machining, which may contribute to lower production costs.

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REFERENCES

1. Grzesik W., (2018), *Hybrydowe procesy skrawania wspomagane mediami technologicznymi*, DOI: https://doi.org/10.17814/mechanik.2018.12.186.
2. Iqbal A., Saelzer J., Nauman M., Biermand D., (2024), *Milling of nickel-based superalloys using throttle cryogenic cooling and micro-lubrication*, ESAFORM, Materials Research Proceedings, 41, 2093-2102.
3. Zhang H., Dang J., An Q., Ming W., Chen M., Zhang J., (2022), *Investigation of machinability in milling of Inconel 718 with solid Sialon ceramic tool using supercritical carbon dioxide (scCO2)-based cooling conditions*, Ceramics International, 48, 4940–4952.
4. Hong S., Ding Y., (2001), Cooling *approaches and cutting temperatures in cryogenicmachining of Ti-6Al-4V*, International Journal of Machine Tools & Manufacture, 41, 1417–1437.
5. Hyeong J., Lee S., Kim S., (2024), Exploring *the diffusion wear mechanism between SiAlON and Inconel 718: Interfacial reactions and thermal properties in diffusion couples*, Ceramics Int., 50, 32670–32677.
6. Prassan S., Navneet K., Amit A., Nishkarsh S., (2022), *Comparison of LN2 and LCO2 based on machining performance indicatorsfor drilling Inconel 718*, Journal of Manufacturing Proc., 81, 444–466.
7. Wang Z., Rajurkar P., (2000), *Cryogenic Machining of Hard-to-Cut Materials,* Wear, 239,168-175.
8. *Gases characteristic cards*, (2024), Available from https://www.linde-gaz.pl/shop/LINSafetyDataSheetsView?catalogId=3074457345616682118&langId=-22&storeId=715849386, Accesed: 23/05/2024,
9. Khan A., Ahmed M., (2008), *Improving tool life using using cryogenic cooling*, Journal of Materials Processing Technology, 196 (1–3), 149–154.
10. Wang Z., Rajurkar K., Fan J., Lei S., Shin Y., Petrescu G., (2003), *Hybrid machining of Inconel 718*, International Journal of Machine Tools and Manufacture, 43, 1391–1396.
11. Venugopal K., Paul S., Chattopadhyay A., (2007), *Tool wear in cryogenic turning of Ti–6Al–4V alloy*, Cryogenics, 47, 12–18.
12. *DIPS System description, (2023)*. Available from https://digitable.co.jp/dips/. Accesed: 15.10.2024.
13. Zeilmann R., Fontanive F., Soares R., (2017), *Wear mechanisms during dry and wet turning of Inconel 718 with ceramic tools*. The Int. Journal of Advanced Manufacturing Technology, 92, s. 2705–2714.
14. Certificate of Quality no AC/5524, order A2019522SSS, confirmation 207990, manufacturer/supplier Italfond Stainless and superalloys, 21/11/2019 r.
15. Insert characteristic, Available from https://www.kennametal.com/us/en/products/p.negative-inserts-rngn.4146441.html#tad, Acessed: 15.10.2024.
16. GeniCore Handout, (2023), available from: https://genicore.eu/materials/, Accessed: 19/10/2023.
17. Coolant safety data sheet (2018), Available from https://home.quakerhoughton.com/hocut-4940-technical-data-sheet/, Acessed:14.10.2024.

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