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Effects of application of different cooling methods during the drilling of Inconel 718

SUMMARY

This paper deals with the subject of various types of cooling during drilling of Inconel 718. The wear indicator of VBB (abrasion on the flank surface) and the chips generated during drilling were compared. Three drilling methods have been compared: with a cutting fluid, gas cooled with carbon dioxide, and without cooling. It was found that cooling with the use of liquid best influences the durability of the tool, however, gas cooling also reduces wear and facilitates chip removal.

Key words: drilling, Inconel 718, cooling, CO_2, tool wear, chip formation.

Introduction

The cooling during machining is often unavoidable if the process ought to be efficient. Coolant in mechanical processing is used to:

- reduce the temperature in the cutting zone, this is important because the heightened temperature is the reason of the increase in the dimensions of the tool and the workpiece, which results in dimensional and shape inaccessibility of the workpiece. The temperature affect a linear extension of the tool, which results changes in the cut depth and the curvilinear movement of the tool[1].

[1] J. Jóźwik, J. Lipski, *Błędy obróbki skrawaniem i ich prognozowanie z wykorzystaniem sztucznych sieci neuronowych*, Wydawnictwo Politechniki Lubelskiej, Lublin 2014, s. 24–30.

- reduce the coefficient of friction between the workpiece, the chip and the tool, which effect mainly of reducing the cutting forces.
- improve the parameters of the surface layer;
- facilitate removal of chips from the cutting zone;
- obstruct the formation of build-up.

Overview of different cooling methods

The most commonly used cooling fluids are liquids, which can be distinguished to three groups: pure oils, gases and water mixtures, among them oil, semi-synthetic and synthetic emulsions.

Less frequently gases are used as a coolant. Under normal conditions they are characterized by low thermal conductivity, but in the state of strong decompression they absorb large amounts of heat from the environment. Gas cooling has a number of advantages over conventional cooling, i.e. using cutting fluids. Among other things there is no problem of utilizing coolant after use. In the gas tank, the pH does not change as it can be occur during longer work with unspecified liquid coolant. Molds and bacteria can develop in aqueous solutions. In addition, the products obtained with gas cooling are suitable for aerospace or medical applications, because they are not contaminated, for example, with biological agents.

Most often used gases used for cooling are: air, nitrogen and carbon dioxide, less frequently used are argon and helium[2]. Exploitation of liquid nitrogen as a cooling medium has been studied for many years[3]. It has a number of advantages, including it is colorless, odorless, tasteless and non-toxic. It has been successfully used in the machining of titanium, where the tool wear has been significantly reduced due to liquid nitrogen cooling[4], and Inconel[5] . However, the use of liquid nitrogen is also associated with several problems, including high costs of labor protection due to intensive cooling of machine components and tools; high costs are also associated with the apparatus for supplying coolant to the cutting zone. It should be remembered that in such low temperatures the properties of both the workpiece and the tool changes.

As an alternative to liquid nitrogen, carbon dioxide, which does not reach such low temperatures can be used. Carbon dioxide can be stored in pressure tanks. Work safety expenses are much lower here. There are works which shows that the wear of the flank surface decreased and was uniformly distributed along the cutting edge for machining titanium alloys with CO_2-snow cooling compared to emulsion cooling[6],

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[2] A.E. Elshwain, N. Redzuan, *Effect of Cooling/Lubrication using Cooled Air, MQL + Cooled Air, N2 and CO2 Gases on Tool Life and Surface Finish in Machining – A Review*, „Advanced Materials Research" 2014, Vol. 845, s. 889–893.

[3] K. Uehara, S. Kumagai, *Chip formation, surface roughness and cutting force in cryogenic machining*, „Annals of CIRP" 1969, Vol. 17(1), s. 409–416.

[4] Z. Hamedon, T. Mon, S. Sharif, V. Venkatesh, A. Masri, E. Sue-Rynley, *Performance of nitrogen gas as a coolant in machining of titanium*, „Advanced Materials Research" 2011, Vol. 264–265, 962–966.

[5] A.K. Ahsan, I.A. Mirghani„ *Improving tool life using cryogenic coolig*, „Jurnal of Materials Processing Technology" 2008, Vol. 196, s. 149–154.

[6] C. Machai, Biermann D., *Machining of β-titanium-alloy Ti–10V–2Fe–3Al under cryogenic conditions: Cooling with carbon dioxide snow*, „Journal of Materials Processing Technology" 2011, Vol. 211, s. 1175–1183.

and in[7] it was shown that the surface roughness of the shaft made of Inconel 718 was reduced after turning with the use of. CO_2 gas cooling, compared to dry turning. However, the same tests shows increased microhardness of surfaces with carbon dioxide gas cooling.

A combination of carbon dioxide cooling with minimal lubrication is also used, which results in additional lubrication. As a result, an almost dry chip and the product which not need to be cleaned are obtained[8].

Inconel 718 is a hard-to-cut material mainly due to induration during processing and because of thermal conductivity, definitely lower than commonly used steel alloys, and high thermal expansion. For this reason, during machining Inconel, the cutting tool is exposed to damage and quickly tool wear[9]. Because the temperature in the cutting zone is much higher than at work with conventional materials, it forces the use of coolant to dissipate the heat generated. Alloys such as Inconel 718 tend to create build-ups and chips on the machined surface, which significantly decrease the quality of the geometric structure of the surface[10].

One of the typical wear during machining of Iconel 718 is notch wear of the insert caused by metal embossing with the insert cutting edge, the characteristic double chip is also present during this process. It often happens that the processing parameters recommended by the producers turn out to be inappropriate and, as a result, the unprofitable form of the chip is obtained[11]. Bounding between the chip and the flank surface by the occurrence of high temperatures or chemical affinity, during the machining cause two wear mechanisms. The abrasion wear occurs mainly on flank surface and the groove wear occurs on the minor flank surface. When using cemented carbide tools with a cobalt matrix, nickel and iron diffusion on the grain boundaries was observed. As a result of this diffusion, the connection between the matrix and the carbide is destroyed, which results in detaching of the carbide grains[12].

Experimental details

The machined material was a shaft made of Inconel 718 AMS 5662, it is a hardening nickel-chromium alloy. The exact composition is shown in Table 1. It is annealed at 980°C for an hour, then cooled in air or argon. Aging is carried out at a temperature of 720°C for eight

[7] N.G. Patil, A. Asem, R.S. Pawade, D.G. Thakur, P.K. Brahmankar, *Comparative study of high speed machining of Inconel 718 in dry conditio and by using compressed cold carbon dixide gas as coolant*, „New Production Technologies in Aerospace Industry" – 5th Machining Innovations Conference, „Procedia CIRP" 2014, Vol. 24, s. 86–91.

[8] K. Busch, C. Hochmuth, B. Pause, A. Stoll, R. Wertheim, *Investigation of cooling and lubrication strategirs for machining high-temperature alloys*, „Procepia CIRP" 2016, Vol. 41, s. 835–840.

[9] E. Ezugwu, *Key inprovements in difficult-to-cut aerospace superalloys*, „International Journal of Machine Tools and Manufacture" 2005, Vol. 45, s. 1353–1367; Kieruj P., Przestacki D., Chwalczuk T., *Determination of emissivity coefficient of heat-resistant super alloys and cemented carbide*, „Archives of Mechanical Technology and Materials" 2017, Vol. 36, Issue 1., s. 30–34.

[10] T. Chwalczuk, P. Twardowski, P. Keruj, P. Szablewski, *Dokładne toczenie stopu Iconel 718 ostrzami CBN*, „Zeszyty Naukowe Politechniki Rzeszowskiej", „Mechanika" 2017, Vol. 295 nr 89, s. 307–314.

[11] B. Słodki, *Selected sequences of chip breaking process in turning nickel based superalloys*, „Advancer in Manufacturing Science and Technogy" 2011, Vol.35 (2), s. 29–36.

[12] Y. Liao, R. Shiue, *Carbide tool wear mechanism in turning of Inconel 718 superalloy*, „Wear" 1996, Vol. 193, s. 16–24.

hours, then the temperature is lowered to 620°C for two hours and returned for a further eight hours to a temperature of 720°C. After this treatment, the material has a hardness of approx. 47 HRC. Nickel-based superalloys are typically used in the aerospace industry, as gas turbines, for parts of space shuttles, nuclear reactors. They are characterized by high durability at elevated temperatures, wear and corrosion resistance, excellent creep resistance at temperatures up to 700°C[13].

Table 1. Chemical composition of the Inconel 718 alloy [own elaboration]

element / percentage	Ni	Cr	Nb	Mo	Ti	Al	Co	Cu	C	Si	Mn	P	S	B	Fe
Min. %	50	17	4,75	2,8	0,65	0,2	—	—	—	—	—	—	—	—	—
Max.%	55	21	5,5	3,3	1,15	0,8	1	03	0,08	0,35	0,35	0,015	0,015	0,006	rest

Spiral cutting length

The concept of spiral cutting length was introduced by *Sandvik Coromat* for machining heat-resistant alloys based on iron, nickel or cobalt. The need to introduce this variable resulted from the low durability of the blades during the processing of heat resistant super alloys (HRSA). In a simplified, It is calculated as the product of the circumference of the turned object, i.e. the path that the tool describes during the cutting of the element and the length of the longitudinal movement made by the tool during operation. For longitudinal turning, it is calculated from equation (1)[14]:

$$SCL = \frac{D_{m1} \cdot \pi}{1000} \cdot \frac{l_m}{f} \tag{1}$$

Where:

SCL – spiral length of the cutting path (m),

D_{m1} – object diameter after turning; $D_{m1} = D_m - 2a_p$ (mm)

l_m – linear length of cut (mm),

The researches were carried out on a DMG Mori 310 Ecoline CNC lathe. During the tests, drilled in two identical shafts with a diameter of Ø 54 mm and length of 71.5 mm, made of Iconel 718 AMS 5662. In the research a indexable inserts drill Sandvik Coromant 880-D2500L25-03 was used, this drill has an internal coolant supply, moreover, it has been modified to enable the gas cooling. The drill is shown in Figure 1. Two cutting-inserts were used, central 880-05 03 05H-C-LM 1144 made of fine-grained cemented carbide coated with PVD ($TiAlN+(AlCr)_2O_3$) and external insert 880-05 03 W08H-P-LM 4044, also made of fine-grained cemented carbide with PVD ($TiAlN_2$) coating.

[13] D. Ulutan, T. Özel, *Machining induced surface integrity in titanium and nickel alloys: a review*, „International Journal of Machine Tools and Manufacture" 2011, Vol. 51, s. 250–280.

[14] B.A.E. Hernandez, T.,J. Beno, A. Wretland, *Analsis of tool utilization from material removal perspective*, „Science Direct" 2015, Procedia CIRP 29, s. 109–113; https://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/technical%20guides/en-us/c-2920-034.pdf].

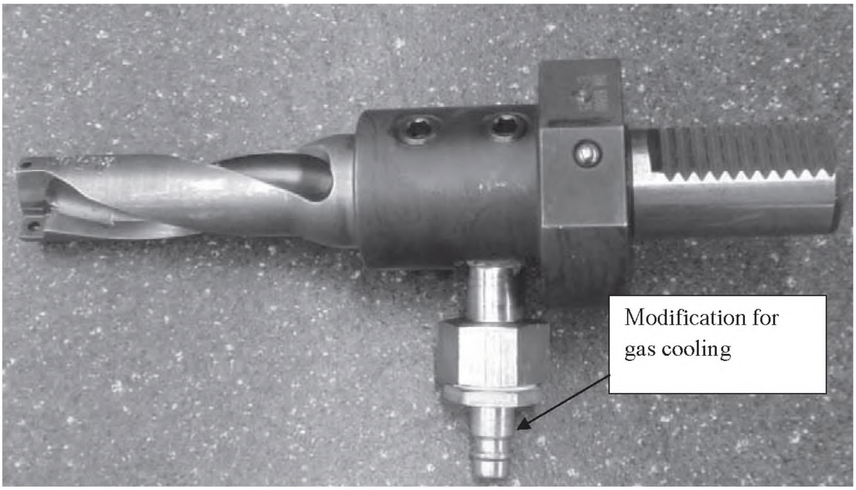

Figure 1. Drill modified for gas cooling

Source: own elaboration.

The test was carried out with constant cutting parameters: rotation speed n = 446 mm·rev^{-1}, feed per revolution f = 0,08 mm·rev^{-1}. The hole was made to a depth of h = 5 mm, in three stages $h_{1,2}$ = 2 mm and h_3 = 1 mm. At the end of each stage, the average abrasion width was measured on the flank surface (VB_B). Three series of tests were carried out: with flood cooling, with carbon dioxide cooling and dry. For the conventional cooling, a 5% Cimtech A31F liquid from Cincool with demineralized water was used, during the carbon dioxide cooling process, the mass gas pressure was p= 4 bars, the flow through the nozzle was 0,02355 kg·min^{-1}. In addition to the wear measurement, the form of the chips were also compared.

Results and their discussion

Table 2 shows the results of VB_B wear measurements for various cooling methods.

Table 2. VB_B wear values for various cooling methods

Nr	Conventional cooling		Carbon dioxide gas cooling		Withouth cooling				
	$VB_{B\_}zew$	$VB_{B\_}wew$	$VB_{B\_}zew$	$VB_{B\_}wew$	$VB_{B\_}zew$	$VB_{B\_}wew$	h	H	SCL
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[m]
1	0,06	0,07	0,08	0,03	0,1	0,07	2	2	2
2	0,08	0,08	0,09	0,04	0,14	0,09	2	4	3,9
3	0,1	0,09	0,11	0,04	0,16	0,11	1	5	4,9
4	0,13	0,11	0,13	0,07	0,23	0,17	2	7	6,9
5	0,15	0,11	0,16	0,1	0,24	0,18	2	9	8,8

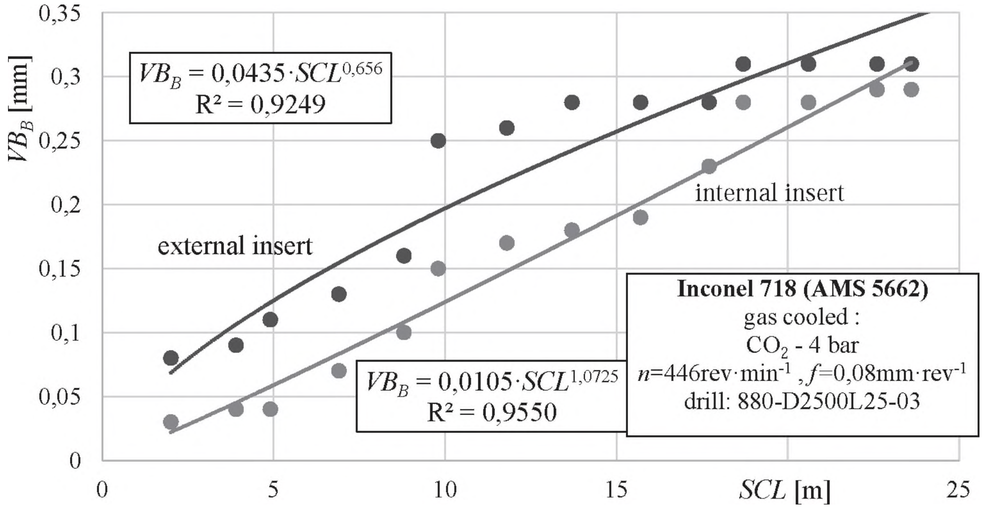

Figure 3. Dependence of VB_B wear of spiral cutting length *SCL* for gas cooled machining

Source: own elaboration.

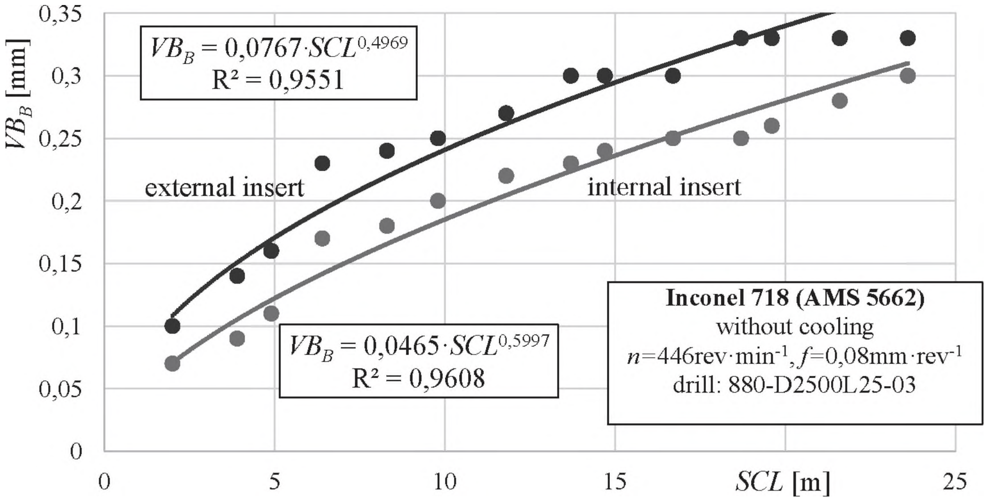

Figure 4. Dependence of VB_B wear of spiral cutting length *SCL* for machining without cooling

Source: own elaboration.

It can be noticed that the spiral cutting length was an appropriate criterion for this process as the correlation coefficients in each case were above $R^2 = 0{,}9$. By comparing the above graphs, it can be seen that wear does not occur uniformly with all cutting strategies. The difference in the wear progression of the central insert is clearly visible. With liquid cooling (Figure 2), the wear is lower and increases more gently than in other tests, this is probably due to the lower friction. The wear progression from the spiral cutting length for dry cutting (Figure 4) are identical in shape. Figure 5 shows a comparison of the final abrasion width for all performed tests.

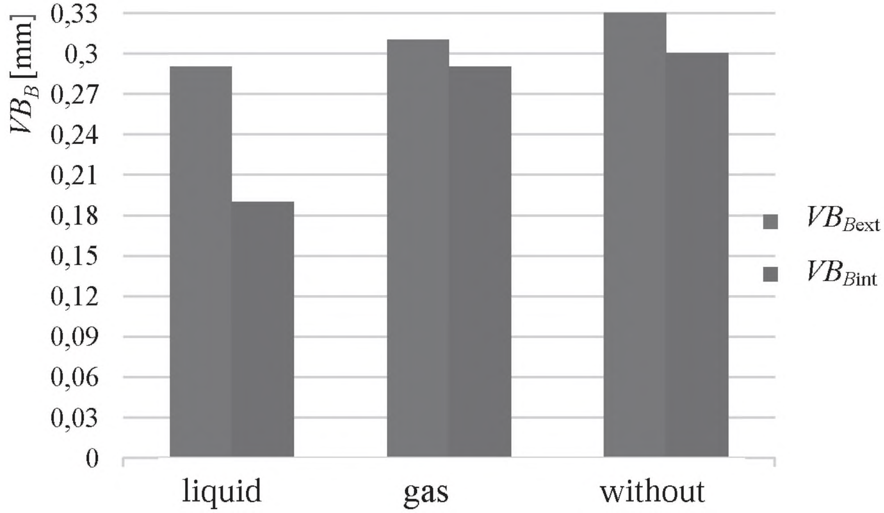

Figure 5. Comparison of VB_B final wear for internal and external inserts after cutting with various cooling methods

Source: own elaboration.

For each cooling method, the wear of the central insert was smaller than on the external, this is due to the lower cutting speed on this insert. Figure 5 shows that gas cooling reduces tool wear compared to dry cutting.

Figs. 6, 7, 8 shows respectively the final chip forms for the external inserts for cutting with flood cooling, gas cooling and non-cooling. Figure 9 shows the chip form of the central insert and it was the same regardless of the cooling method.

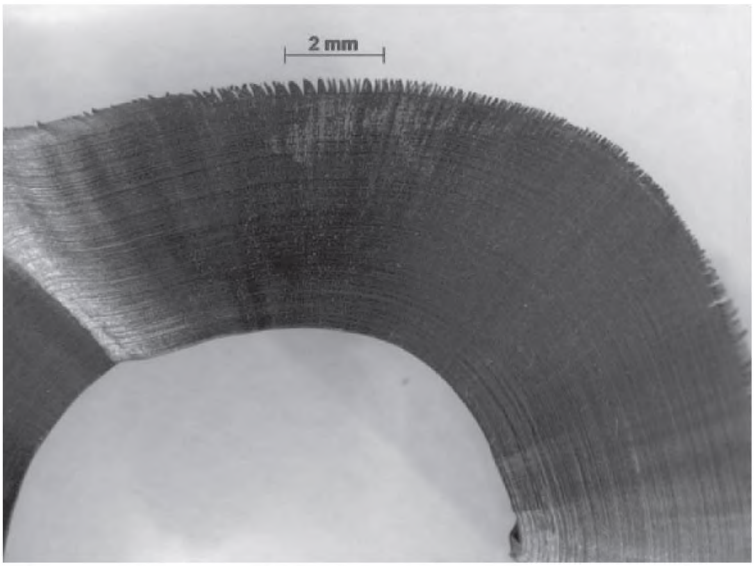

Figure 6. Chip after machining with cooling emulsion for an external insert

Source: own elaboration.

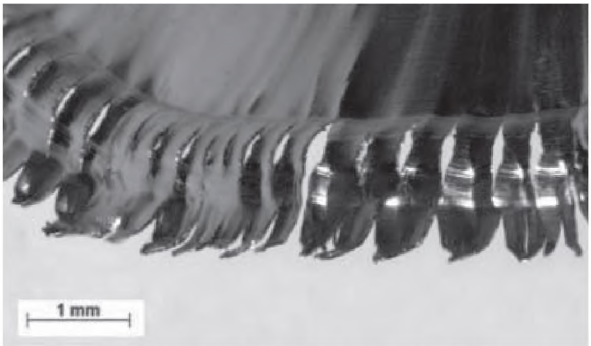

Figure 7. Chip after machining with carbon dioxide cooling for an external insert

Source: own elaboration.

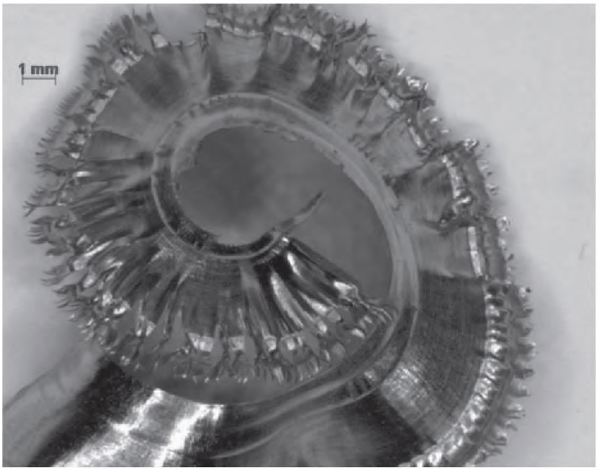

Figure 8. Chip after machining without cooling for an external insert

Source: own elaboration.

Figure 9. Chip for central insert

Source: own elaboration.

As can be seen in the above pictures (Figure 6, 7, 8), a different form of the chip was obtained depending on the method of cooling. The pictures presented present the final parts of the chips. Chip segmentation occurred during each type of cooling at drilling depths of 5mm (last stage) regardless of tool wear. In each case, a spiral chip was obtained on the external insert, however after dry cutting (Figure 8), it was the most undulated, which may suggest a problem with chip removal from the hole. A slight wave was also present on the chip obtained from the insert gained from machining under gas cooling, which is probably caused by the lack of lubrication and harder chip removal than during machining with flood cooling, where the chip was smooth. It is possible to determine the chip segmentation frequency from the below formula (2)[15]:

$$F_{hzCG} = \frac{100V_S}{6\Delta x_{Chip}} \quad (2)$$

Where:
F_{hzCG} – formation frequency of sawtooth chip based on chip geometry [Hz]
V_S – velocity of chip sliding on the tool rake face [$m \cdot min^{-1}$]
Δx_{Chip} – distance between two chip peak, chip vault [mm].
Figure 10 shows an illustration of the definition of Δx_{chip}

Figure 10. Graphical definition of ΔX_{Chip}

Source: own elaboration.

Afterwards, according to the formula (3), the slide velocity V_S can be determined, depending on the cutting parameters[16]:

$$V_S = \frac{v_c f a_p}{e_c l_c} \quad (3)$$

Where:
v_c – cutting speed [$m \cdot min^{-1}$]
f – feed per revolution [$mm \cdot rev^{-1}$]
a_p – depth of cut [mm]
e_c – mean chip thickness [mm]
l_c – width of the chip [mm].
As the depth of cut was not determined in the case of drilling, the external insert in the indexable inserts drill can be calculated from the formula (4):

$$a_p = b\sin\kappa_r \quad (4)$$

[15] S. Behadi, T. Mabrouki, J.F. Rigal, L. Boulanouar, *Experimental and numerical study of chip formation during straight turning of hardened AISI 4340 steel*, „Journal of Engineering Manufacture" 2005, s. 515–524.
[16] Ibidem.

b – width of the cutting layer [mm]
κ_r – entering angle [°]

For the used indexable inserts drill (880-D2500L25-03), the entering angle is κ_r=88°, and the width of the cutting layer is equal to the width of the insert, so b = 8,9 mm.
Figure 11 shows a section of a cutting layer for an external insert.

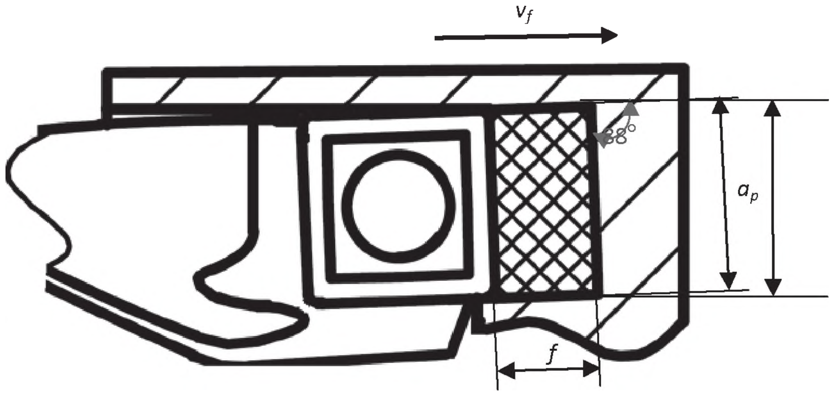

Figure 11. Cross-section of the cutting layer for an external insert
Source: own elaboration.

Combining 2, 3, 4 patterns, you can obtain the final pattern for the frequency of chip segmentation in the form (5):

$$F_{hzCG} = \frac{100 V_c f b \sin\kappa_r}{6 \Delta x_{Chip} e_c l_c} \quad (5)$$

In the case of flood cooling, the obtained chip is a sawtooth chip and has only one frequency of segment formation. On the other hand, with the chips obtained from machining with carbon dioxide cooling and without cooling, there are two frequencies of creating segments, first as in the case of liquid cooling, i.e. creating a sawtooth chip and the second from chip breaking. In the first case they are similar for each cooling method, the results are presented in Table 3.

Table 3. Frequency of chip segmentation in various cooling methods

cooling medium	v_c [mm·min^{-1}]	f [mm·rev^{-1}]	b [mm]	e_c [mm]	l_c [mm]	Δx_{chip} [mm]	F_{hzCG} [Hz]
liquid	35	0,08	8,9	6,45	0,21	0,21	1459
gas	35	0,08	8,9	6,48	0,22	0,19	1532
without	35	0,08	8,9	6,42	0,21	0,22	1469

Source: own elaboration.

The segmentation frequency for drilling is around 1500 Hz, this frequency is not affected by the cooling method.

Conclusions

1. Carbon dioxide cooling reduces tool wear compared to dry cutting, however, compared to liquid cooling, tool wear is higher. This is due, among other things, to the lack of lubrication between the flank surface and the workpiece. However, gas cooling reduces only the temperature in the cutting zone, which already allows for a slight reduce of the tool wear.
2. The wear of the central insert is smaller than the external one due to the lower cutting speed. In addition, lubrication with liquid cooling further reduces its wear. With the external insert, there was no such significant difference between drilling with and without lubrication.
3. Drilling with the use of cutting fluid facilitates chip removal. During flood cooling, no bending or breaking of the chip inside the material took place, only segmentation occurred (formation of sawtooth chip). The most unfavorable chip was created during dry drilling (Figure 8), it was the most wavy one, can expect chip wedging at larger drilling depths. The chip obtained with carbon dioxide cooling was also segmented due to breaking, however, the chip was not so undulated (Figure 7). It can be concluded, that the gas introduced under pressure facilitates chip removal even without lubrication.
4. Independently on the type of cooling and the tool wear, the chip was segmented. This took place during the final part of the hole drilling. This is probably related to the reduction of process stability during drilling a deeper holes. The segmentation frequency was similar for all chips, regardless of the type of cooling. Chip segmentation occurred only for the outer insert, Chip segmentation occurred only for the outer insert.

Acknowledgments

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Bibliography

Ahsan A. K., Mirghani I. A.,, *Improving tool life using cryogenic coolig*, „Jurnal of Materials Processing Technology" 2008, Vol. 196, s. 149–154.

Behadi S., Mabrouki T., Rigal J-F., Boulanouar L., , *Experimental and numerical study of chip formation during straight turning of hardened AISI 4340 steel*, „Journal of Engineering Manufacture" 2005, s. 515–524.

Busch K., Hochmuth C., Pause B., Stoll A., Wertheim R., *Investigation of cooling and lubrication strategirs for machining high-temperature alloys*, „Procepia CIRP" 2016, Vol. 41, s. 835–840.

Chwalczuk T., Twardowski P., Keruj P., Szablewski P., *Dokładne toczenie stopu Iconel 718 ostrzami CBN*, „Zeszyty Naukowe Politechniki Rzeszowskiej", „Mechanika" 2017, Vol. 295 nr 89, s. 307–314.

Elshwain A. E., Redzuan N., *Effect of Cooling/Lubrication using Cooled Air, MQL + Cooled Air, N2 and CO2 Gases on Tool Life and Surface Finish in Machining – A Review*, „Advanced Materials Research" 2014, Vol. 845, s. 889–893.

Ezugwu E., *Key inprovements in difficult-to-cut aerospace superalloys*, „International Journal of Machine Tools and Manufacture" 2005, Vol. 45, s. 1353–1367.

Hamedon Z., Mon T., Sharif S., Venkatesh V., Masri A., Sue-Rynley E., *Performance of nitrogen gas as a coolant in machining of titanium*, „Advanced Materials Research" 2011, Vol. 264–265, 962–966.

Hernandez B. A. E., Beno T., J., Wretland A., *Analsis of tool utilization from material removal perspective*, „Science Direct" 2015, Procedia CIRP 29, s. 109–113.

Jóźwik J., Lipski J., *Błędy obróbki skrawaniem i ich prognozowanie z wykorzystaniem sztucznych sieci neuronowych*, Wydawnictwo Politechniki Lubelskiej, Lublin 2014, s. 24–30.

Kieruj P., Przestacki D., Chwalczuk T., *Determination of emissivity coefficient of heat-resistant super alloys and cemented carbide*, „Archives of Mechanical Technology and Materials" 2017, Vol. 36, Issue 1., s. 30–34.

Liao Y., Shiue R., *Carbide tool wear mechanism in turning of Inconel 718 superalloy*, „Wear" 1996, Vol. 193, s. 16–24.

Machai C., Biermann D., *Machining of β-titanium-alloy Ti–10V–2Fe–3Al under cryogenic conditions: Cooling with carbon dioxide snow*, „Journal of Materials Processing Technology" 2011, Vol. 211, s. 1175–1183.

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Słodki B., *Selected sequences of chip breaking process in turning nickel based superalloys*, „Advancer in Manufacturing Science and Technogy" 2011, Vol.35 (2), s. 29–36.

Uehara K., Kumagai S., *Chip formation, surface roughness and cutting force in cryogenic machining*, „Annals of CIRP" 1969, Vol. 17(1), s. 409–416.

Ulutan D., Özel T., *Machining induced surface integrity in titanium and nickel alloys: a review*, „International Journal of Machine Tools and Manufacture" 2011, Vol. 51, s. 250–280.

https://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/technical%20guides/en-us/c-2920-034.pdf].

STRESZCZENIE

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Efekty zastosowania różnych sposobów chłodzenia podczas wiercenia Inconelu 718

Niniejsza praca porusza temat różnych rodzajów chłodzenia podczas wiercenia Inconelu 718. Porównano ze sobą zużycie VBB (starcia na powierzchni przyłożenia) oraz powstający przy wierceniu wiór. Porównano ze sobą trzy sposoby wiercenia: z cieczą chłodząco-smarującą, z chłodzeniem gazowym dwutlenkiem węgla oraz bez chłodzenia. Stwierdzono, że chłodzenie z wykorzystaniem cieczą najlepiej wpływa na trwałość narzędzia, jednak chłodzenie gazem również zmniejsza jego zużycie oraz ułatwia odprowadzenie wióra.

Słowa kluczowe: wiercenie, Inconel 718, chłodzenie, CO2, zużycie narzędzia, tworzenie wióra.

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