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Article

High Speed Finish Turning of Inconel 718 Using PCBN Tools under Dry Conditions

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Abstract: Inconel 718 is a superalloy, considered one of the least machinable materials. Tools must withstand a high level of temperatures and pressures in a very localized area, the abrasiveness of the hard carbides contained in the Inconel 718 microstructure and the adhesion tendency during its machining. Mechanical properties along with the low thermal conductivity become an important issue for the tool wear. The finishing operations for Inconel 718 are usually performed after solution heat treatment and age hardening of the material to give the superalloy a higher level of hardness. Carbide tools, cutting fluid (at normal or high pressures) and low cutting speed are the main recommendations for finish turning of Inconel 718. However, dry machining is preferable to the use of cutting fluids, because of its lower environmental impact and cost. Previous research has concluded that the elimination of cutting fluid in these processes is feasible when using hard carbide tools. Recent development of new PCBN (Polycrystalline Cubic Boron Nitride) grades for cutting tools with higher tenacity has allowed the application of these tool grades in the finishing operations of Inconel 718. This work studies the performance of commercial PCBN tools from four different tool manufacturers as well as an additional grade with equivalent performance during finish turning of Inconel 718 under dry conditions. Wear tests were carried out with different cutting conditions, determining the evolution of machining forces, surface roughness and tool wear. It is concluded that it is not industrially viable the high-speed finishing of Inconel 718 in a dry environment.

Keywords: dry turning; Inconel 718; PCBN; wear

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1. Introduction

In the context of heat-resistant alloys, there has been a noticeable upward trend over recent decades to employ nickel-based superalloys for manufacturing critical components under extreme service conditions. Inconel 718 has become one of the most suitable candidates due to its unique properties at very high temperatures, such as high mechanical and thermal strength, formidable resistance to corrosion, and elevated creep resistance. Therefore, it can be extensively found in gas turbines of jet engines or in steam turbines of nuclear plants (for example, blades, disks, bolts and valves) [1].

Regarding its machinability, Inconel 718 is well known as one of the most difficult materials to cut. Its excellent mechanical and thermal properties at high temperature, coupled with a high work hardening tendency, poor thermal conductivity, chemical reactivity with tool materials, and the abrasive particles contained in its microstructure, produce notable wear of the cutting tool [2,3]. The cutting temperatures achieved at the cutting edge can be up to 1200 °C [4]. Furthermore, the high cutting forces developed during machining, due to its hardness at high temperatures, subject the superalloy to elevated mechanical stress at the interface between the workpiece and the cutting edge [5]. Thus, mechanical, metallurgical, thermal, or topographic alterations may be easily produced when machining this alloy, which may compromise the surface integrity of the final workpiece.

Under these peculiar circumstances of extreme thermal and mechanical stresses, the cutting tool materials commonly used for finish turning of nickel-based alloys are carbides and, recently, cubic boron nitride (CBN) [6]. Cemented carbide tools are employed at low speeds due to pronounced tool wear at cutting speeds over 30 m/min [7]. In comparison to uncoated carbide tools, single or multiple layers of cement coating deposited on cemented carbide tools increase tool wear resistance, allowing for cutting speeds close to 100 m/min [8,9].

Recently, a new technique has been developed for finish turning Inconel 718: employing PCBN as the tool material with a low or medium CBN content (usually 50–65%) and a ceramic binder. These materials preserve hardness at high temperatures, increasing tool toughness and allowing a sharper cutting edge for finishing operations. PCBN cutting tools can be used at high cutting speeds [10,11], increasing productivity, largely because of PCBN's ability to maintain hardness at the temperatures reached during machining. However, the high cost of PCBN tools hinders their implementation in industry [6,12].

Under wet conditions and high cutting speeds, adhesion and diffusion are dominant wear mechanisms for PCBN tools, due respectively to high friction and chemical affinity; abrasion wear is also a concern [10]. Costes et al. (2007) also found that CBN cutting tools with low or medium CBN content and fine grain had greater wear resistance and higher tenacity.

Tanaka et al. (2016) investigated the wear behavior of two PCBN tools with different CBN content when machining Inconel 718, and concluded that the dominant wear mechanism at high cutting speeds was diffusion [13]. Furthermore, recent developments associated with new binders, coats, grain size refinements, or CBN content have shown increased tool wear resistance [13,14]. However, further investigations need to be performed since machining assessment with these novel PCBN tools in nickel-based alloys is still unclear and some controversial can be found in the literature.

In general, due to the low machinability of superalloys, the use of cutting fluid is highly recommended to decrease friction, help with the chip disposal and reduce the temperatures reached during the machining of Inconel 718 [15]. However, increasing concern by governments and society about environmental sustainability of industrial activities has driven manufacturers to implement alternative, greener techniques to be used instead of traditional cutting fluids [16]. Moreover, besides the damage to the environment, the employment of cutting fluids is very costly, not only because of the cost of their acquisition but also because of the costs associated with cleaning workpieces and waste and disposal management [17]. Minimizing the quantity of lubricants and employing biodegradable cutting fluids have recently decreased the environmental impact of machining Inconel 718 and shown better tool performance [18]. However, there is no information regarding the tool wear and tool life of PCBN inserts when machining Inconel 718 in a dry environment. In a previous work, the authors studied the performance of carbide tools in dry finishing turning of Inconel 718, obtaining a tool life of the order of 20min for competitive cutting conditions [19].

For the present work, dry machining tests with commercial PCBN tools were performed under different cutting conditions to evaluate the viability of eliminating cutting fluid in finishing turning of Inconel 718 with PCBN tools. At the same time, the behavior of the PCBN tools was compared with the behavior of carbide tools under the same conditions. Roughness, cutting forces, and tool wear were analyzed to evaluate the performance of the different tools.

2. Experimental Setup

2.1. Working Material and Cutting Tools

The Inconel 718 used in the experiments was hardened by solution heat treatment and aged to reach a state similar to that typically faced by a tool during finishing operations of this superalloy. The hardness of the material was measured at different points, obtaining values from 44 to 45.5 HRc. The chemical composition of the alloy is shown in Table 1.

Table 1. Inconel 718 composition.

Element	Ni	Cr	Fe	Nb	Mo	Ti	Al	Co.	Si	Cu	Mn	C
%	53.02	18.49	18.12	5.40	3.06	0.96	0.55	0.10	0.06	0.05	0.06	0.03

The raw material was a round bar with an external diameter of 100 mm and a length of 130 mm. Six cutting tool grades recommended by five manufacturers for finish turning of Ni-based superalloys were tested. For all the tested tools, manufacturers recommended the use of cutting fluid. However, as mentioned above, the purpose of this work is to perform machining tests under dry conditions in order to verify the viability of avoiding the employment of cutting fluids in the finish turning with PCBN tools.

Machining tests were carried out with coated carbide tools supplied by Seco, specifically recommended for finishing operations of Ni-based superalloys. Positive inserts CCMT 09T304F1 were employed, mounted in tool holder with the code SCLCR 2525M09JET. This configuration corresponds to a tip angle of 80°, tip radius of 0.4 mm, clearance angle of 7°, normal rake and inclination angles of 17°, and rounded edge geometry with a radius of 25 µm. As indicated, previous works have shown that these tools can machine Inconel 718 without cutting fluids under industrially viable conditions. The purpose of these machining tests with coated carbide tools was to allow comparative analysis of dry machining with carbide tools and dry machining at high cutting speeds with PCBN or similar tools.

For finish turning of Ni-based superalloys at high cutting speed (over 200 m/min), only Seco cutting tools manufacturer recommends a PCBN quality denominated CBN170. For this study, this tool was thoroughly studied and a large number of different cutting conditions were evaluated.

Tool manufacturer NTK recommended JP2 grade tools for finishing Inconel 718 at high cutting speeds. Due to confidentially reasons, NTK did not describe the composition of these tools, although NTK indicated that it they are not PCBN tools. However, they are included in this study because they have the same recommended range of cutting parameters as PCBN tools.

Additional machining tests were developed using PCBN tools with a medium-low CBN content provided by the manufacturers Kennametal, Sandvik, and Mitsubishi. These manufacturers do not currently recommend any PCBN quality for finishing Ni-based superalloys. However, when contacted by the authors, they indicated that the tool grades selected were suitable for this type of application and therefore comparable with Seco's CBN170 grade tools. Kennametal, Sandvik, and Mitsubishi PCBN tools were included in the study to verify that they behave similarly under the tested conditions to the CBN170 tool, which was more thoroughly studied.

For the five tools tested at high cutting speed (four PCBN tools and the JP2 grade tool), we employed a negative insert, CNGA120408, mounted in tool holder PCLNR2525M12. This configuration corresponds to a tip angle of 80°, tip radius of 0.8 mm, normal clearance angle of 6° and normal rake and inclination angle of −6°. As listed in Table 2, these tools have different cutting edge geometries.

Table 2. Tool characteristics.

Manufacturer (Grade)	Substrate Composition	Cutting Edge Geometry	Nose Radius	Coating
Seco (TS2000)	Carbide	Round honing: radius 25 µm	0.4	TiAlN + TiN coated
Seco (CBN170)	PCBN (65% CBN, ceramic binder).	Round honing: radius 25 µm	0.8	Without coating
Sandvik (7015)	PCBN (50% CBN, ceramic binder).	Round honing: radius 35 µm	0.8	TiN coated.
NTK (JP2)	Confidential information	Chamfer honing: Honing width 50 µm, Honing angle: −20°.	0.8	TiN coated.
Mitsubishi (MB8025)	PCBN (60% CBN, ceramic binder).	Chamfer honing: Honing width 50 µm, Honing angle: −15°.	0.8	Without coating
Kennametal (KB5625)	PCBN (medium-CBN content, ceramic binder).	Round honing: radius 25 µm	0.8	TiAlN coated

2.2. Experimental Setup and Measuring Instruments

The tests were carried out in a Pinacho Smart Turn 6/165 equipped with a dynamometer (the Kistler 9257B, which can measure the forces and torque in the 3-orthogonal axis), and a high-speed camera (the Photron MINI UX50) to record chip formation and any other important event for analyzing the tools' performance. The high-speed camera recorded 250 frames per second with a resolution of 1280 × 1024. Figure 1 shows the setup of the experiments.

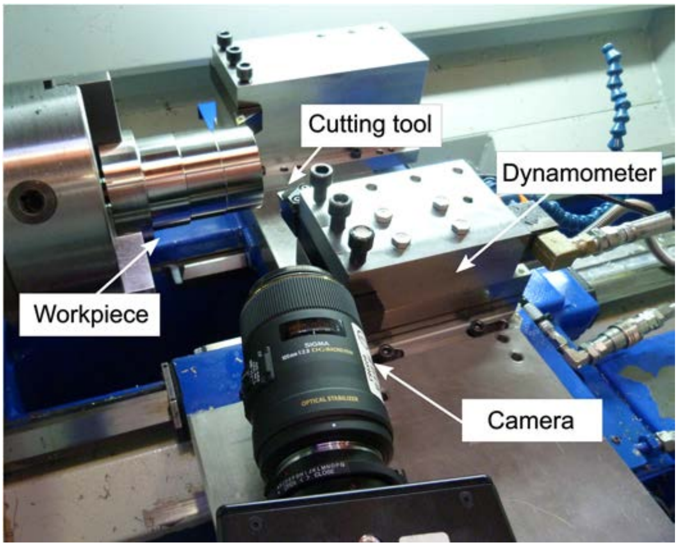


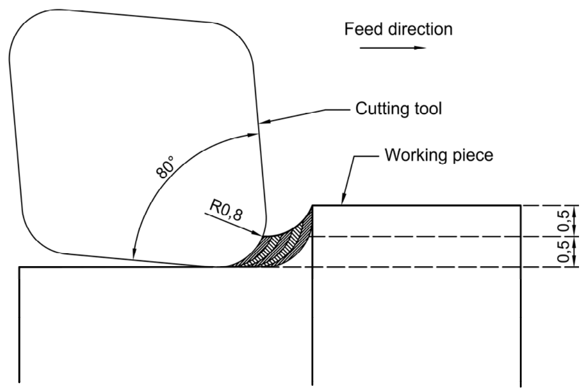
Figure 1. Experimental setup for the tests.

The machined surface quality was determined with a surface roughness gauge, the Mitutoyo Serie SJ-201. An Optika SZR optical microscope was used to evaluate the wear evolution of the cutting tool during the tests. A scanning electron microscope, the (SEM) Philips XL-30, with an EDSDX4i system was used to verify the initial geometry of the fresh cutting edge and to analyze the final state of wear at the end of tool life.

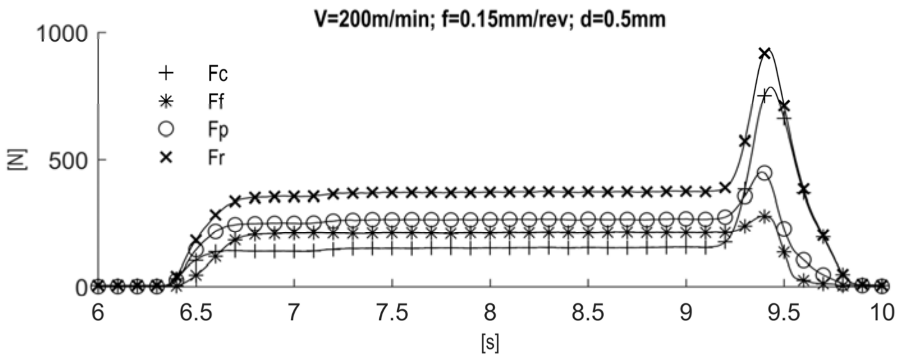
2.3. Experimental Procedure

To check the viability of the use of PCBN tools in dry finish machining of Inconel 718, a cylindrical turning operation was carried out. Shallow cuts (compared to the cutting tool tip radius) were employed due to the relative brittleness of PCBN tools and the characteristics of Inconel 718. Under these circumstances, there was a significant increase in the chip section in the final part of the successive passes of the tests. For example, Figure 2a shows the increased chip section at the end of the second pass, at a cutting depth of 0.5 mm and 0.1 mm of feed. An increased chip section significantly increases the cutting forces and risks premature failure of the cutting tool. Figure 2b shows the peak cutting force (*F*c), feed force (*F*f), back force (*F*p), and resultant force (*F*r), observed at the end of the pass for a turning test with the Seco PCBN tool (CBN170 grade) at a cutting velocity of 200 m/min, a feed of 0.15 mm/rev, and a depth of 0.25 mm. In this case, the resultant force increased more than 100% its nominal value. To avoid this effect, stepped straight turning tests were subsequently performed, in which the length to be machined decreases after each pass.

Tests were carried out following a fixed procedure. One pass was performed and filmed while recording the forces used, after which the surface roughness of the workpiece and the tool wear were evaluated. Tests were stopped once the wear state of the tools became unacceptable. As will be discussed in Section 3.2, different wear mechanisms were observed; hence different criteria were used to declare the end of tool life and so the end of each test. A tool was declared worn if its cutting edge broke, notched, or developed a flank larger than 0.4 mm.



(**a**)



(**b**)

Figure 2. (**a**) Chip section increase at the end of a straight turning pass; (**b**) Force evolution for a test performed at a cutting velocity of 200 m/min, a feed of 0.15 mm/rev, and a cutting depth of 0.25 mm with the CBN170 grade tool.

Tests were developed in three sets. The first set corresponded to tool wear tests using Seco coated carbide tools. The objective of testing this tool was to evaluate the PCBN tools with respect to a tool that already performs well in finish machining of Inconel 718 without the use of cutting fluids [19]. We tested two different cutting speeds, feeds, and depths of passes to check the influence of these parameters in tool performance. For the second set of tests, the viability of Seco PCBN tools in dry machine finishing of Inconel 718 was studied, testing two different cutting speeds. The third test set took into account the best-performing tool of the second set at a cutting speed of 300 m/min; three PCBN tools from other manufacturers and an NTK tool (JP2 grade) were tested at 300 m/min at three cutting depths. For all tests, the selected cutting parameters were in the range of those recommended by the tool manufacturers for finishing operations, however, the manufacturer of the tools recommends the use of cutting fluids to preserve the tool life. Table 3 summarizes the cutting conditions evaluated in 23 cutting tests.

Table 3. Cutting conditions for tool wear tests: Seco coated carbide tool (Set 1); Seco PCBN tool (Set 2) and other manufacturers PCBN tools and JP2 grade (Set 3).

Set of Tests Number	Tool Material (Tool Grade)	Cutting Speed (m/min)	Feed (mm/rev)	Depth of Pass (mm)
Set 1	**Carbide tool** (TS2000, Seco)	35	0.1	0.25
		50	0.1	0.25
				0.5
			0.15	0.25
				0.5
Set 2	**PCBN** (CBN170, Seco)	200	0.15	0.15
				0.25
				0.5
		300	0.15	0.15
				0.25
				0.5
Set 3	**PCBN** (MB8025, Mitsubishi)	300	0.15	0.15
				0.25
				0.5
	PCBN (KB5625, Kennametal)	300	0.15	0.15
				0.25
				0.5
	PCBN (7015, Sandvik)	300	0.15	0.15
				0.25
				0.5
	JP2 (NTK)	300	0.15	0.15
				0.25
				0.5

3. Results

3.1. Experimental Results: Cutting Force Components

The tests measured the three components of total cutting force: cutting force, feed force, and back force. Each condition was tested twice. The obtained variations in the repeated tests were lower than 5%; hence, mean values were chosen to perform all the analysis. The total cutting force, called the resultant force (*F*r), was also analyzed. The specific forces Kc, Kf, Kp, and Kr were calculated by dividing the corresponding force values by the undeformed chip cross section.

Figure 3 compares specific cutting force components and resultant forces obtained experimentally with the Seco TS2000 at the very first instance of the tests (with unworn tools) under different cutting conditions. Values between 3400 and 3800 N/mm^2 were obtained for Kc, which are typical values for Inconel 718 turning processes. The specific resultant force values were between 4000 and 4800 N/mm^2.

For the tested cutting conditions, a significant increment of the specific cutting force was observed if the cutting speed was reduced to 35 m/min. At this cutting speed, Kc is 14% higher than at a speed of 50 m/min. The effect of cutting speed was also visible in the tests performed with the PCBN Seco tool (Set 2), which will be further detailed below. These differences are mainly caused by the higher temperatures achieved in the shearing area, leading to a softening of the material when increasing the cutting speed. At higher speeds, heat generated in the shearing zone has less time to disperse so it is concentrated in that area; on the other hand, the heat that escapes to the workpiece has less time to diffuse to the core of the bar. Thus, the material that has to be removed by the tool retains a higher temperature [15].

Additionally, Figure 3 indicates that the specific resultant force is reduced with the increment of the cutting depth. The variations of the specific forces with the feed are less significant. The effects of feed and cutting depth on the specific forces are related to the geometry of the corresponding non-deformed chip section. In general, by reducing the average non-deformed chip thickness along the edge, specific resultant force increases. This effect is enhanced by the important hardening via plastic deformation of the work material.

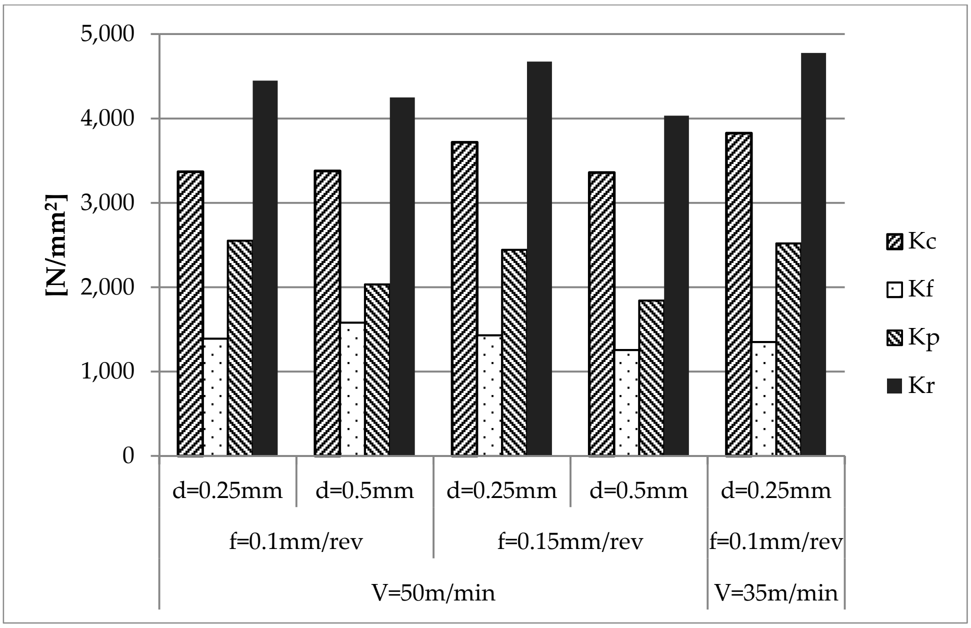


Figure 3. Initial specific cutting force components and specific resultant force in turning tests with carbide tool.

Figures 4 and 5 show the specific cutting force components and resultant forces at the first instances of use for the tested Seco PCBN tool, the remaining PCBN tools, and the JP2 grade tool (Kennametal, Mitsubishi, NTK, and Sandvik toolmakers). To avoid tool wear effect on the measured cutting forces, the plotted specific force values were taken at 1 s of use (enough time to reach force stabilization). However, due to the fragility of this type of tool (especially the sharpest PCBN tools, those manufactured by Seco and Kennametal), the cutting edge deteriorates almost instantaneously under some cutting conditions, producing an unexpected increment of the specific cutting forces, especially those components of cutting force more related to chipping wear (Kp). The indicated wear was the cause of the high cutting forces recorded at a cutting depth of 0.15 mm for Seco and Kennametal tools, where the initial wear of the cutting edge was more relevant (see Figures 4 and 5). Due to the premature cutting edge deterioration, the Kp values were high with respect to the rest of the specific cutting force components.

For cutting depths of pass of 0.25 y 0.5 mm were also observed increments of the specific cutting forces when reducing the depth of cut, however, much more moderate than for the depth of 0.15 mm. The cause is the same as that indicated for the tests with a carbide tool: the effect of the non-deformed chip thickness and the work hardening of the Inconel 718.

Initial specific cutting forces for the studied PCBN tools and the JP2 tool showed significant variation, especially for Kf and Kp. As previously explained, the highest forces were found for the Seco and Kennametal tools, especially when the depth of cut was 0.15 mm; the specific resultant forces were up to 80% higher than those for other PCBN tools. These differences are closely related to the wear suffered by the tool at the first instance of machining. The PCBN tools provided by Kennametal and Seco had the same cutting edge geometry (honing of 25 µm), but the Kennametal tool had a TiAlN coating and the Seco tool was uncoated. The specific cutting forces for the Kennametal tools were slightly higher than those obtained for Seco tools; so apparently, TiAlN coating does not improve the tribological properties of a tool under these cutting conditions.

Smaller forces corresponded to the Sandvik and Mitsubishi PCBN tools. Their cutting edge geometries and tribological conditions were quite different; however, their specific cutting forces are pretty similar. The Sandvik tool possesses a round honing (radius 35 µm) and is TiN coated. The Mitsubishi tool has a chamfer honing (honing width 50 µm, honing angle −15°) and no coating. The minimal thickness of the non-deformed chip and the more negative geometry of the Sandvik tool should have produced higher specific cutting forces; however, these effects were balanced by the minimal friction of the TiN coating.

The specific cutting forces of NTK's JP2 tool were slightly higher, mainly due to its more robust cutting edge geometry (chamfer honing: honing width 50 µm, honing angle −20°).

In general, initial specific cutting force components Kf and Kp were higher for the PCBN and JP2 tools than those obtained with the carbide tools. This difference was due to the higher initial wear suffered by them and the fact that their cutting edge has negative geometry and is less sharp than that of the carbide tool. This edge geometry also explains why Kp had a higher value than Kc. It must be kept in mind that the high specific force in machining with PCBN tools indicates an increased risk of damage to the material, which can be critical in high-responsibility applications in which surface integrity must be controlled.

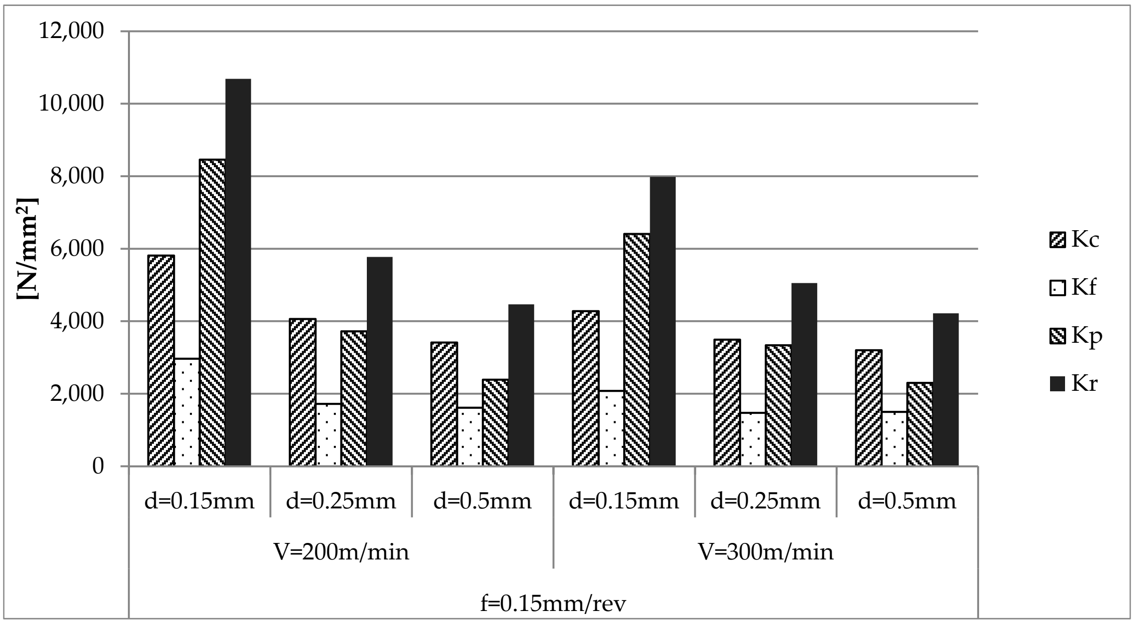


Figure 4. Initial specific cutting force components and specific resultant forces in turning tests with Seco's PCBN tool.

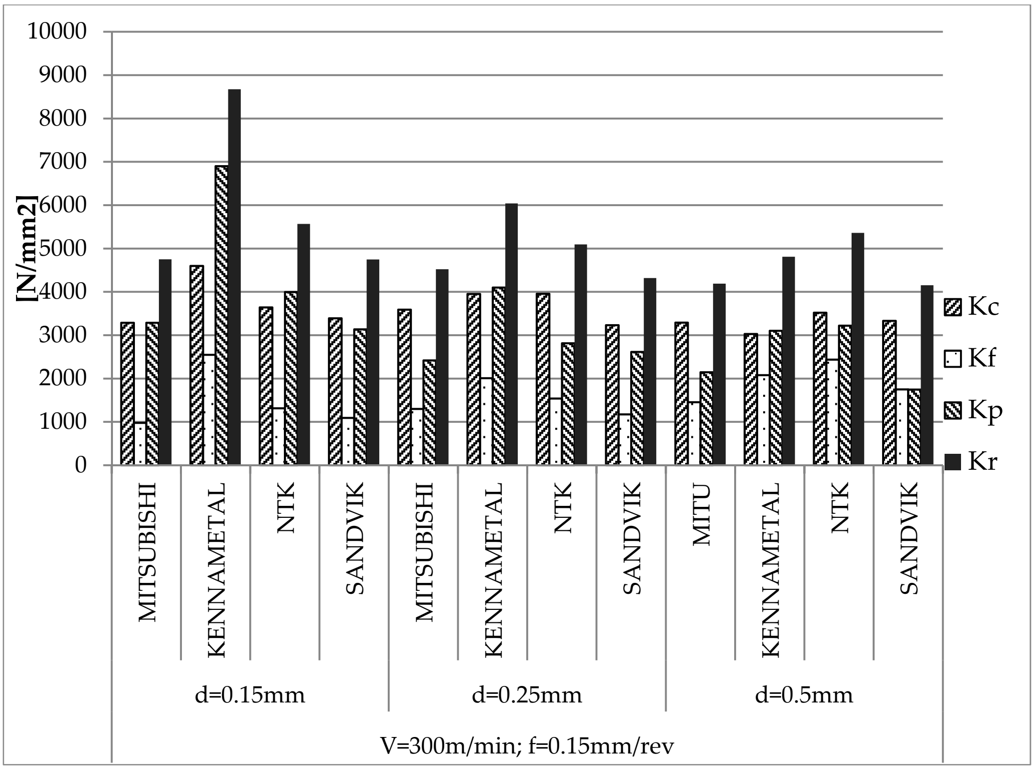


Figure 5. Initial specific machining force components and specific resultant forces in turning tests with different PCBN and JP2 grade cutting tools.

Moreover, reduction of the specific force components is observed with increased cutting speed (see Figure 4). This trend could be caused by the higher temperatures achieved in the shearing area and the consequent softening of the working material.

Figure 6 displays the force evolution with cutting time using the carbide tool (TS2000 grade). Figure 7 shows the force evolution using the Seco PCBN tool (CBN170 grade). Figure 7 does not include the forces recorded during the tests at a cutting depth of 0.5 mm. The high initial wear of the tool causes an unrepresentative relationship of the forces with the machining time.

Initially, the force components presented a reduced upward trend with time of cut for the tests with the carbide tool (see Figure 6). Between 1 and 3 min before reaching the end of tool life, the forces increase sharply, especially the Fp component. It should be noted that this sudden increase of forces does not correspond to a significant increase to the geometrical wear of the tool. Tool wear increases very gradually until the end of life. This result is highly relevant because it demonstrates that the back force can be a tool state indicator. Therefore, back force monitoring could allow the control of this type of process in industrial machining applications.

In contrast, the force evolution with machining time in the PCBN tool tests (see Figure 7) showed a linear trend to the force components throughout the entire test. The back force evolution was faster than the other components. This can be explained by the fact that the edge geometry of PCBN tools is less sharp than that of hard metal tools, and is therefore less sensitive to the wear. In this way, the cutting force evolution is also closely related to the level of wear in turning with PCBN tools. However, there is not a clear change when approaching the end of life. Thus, controlling the end of life by the evolution of these magnitudes would not be direct in comparison to carbide tools.

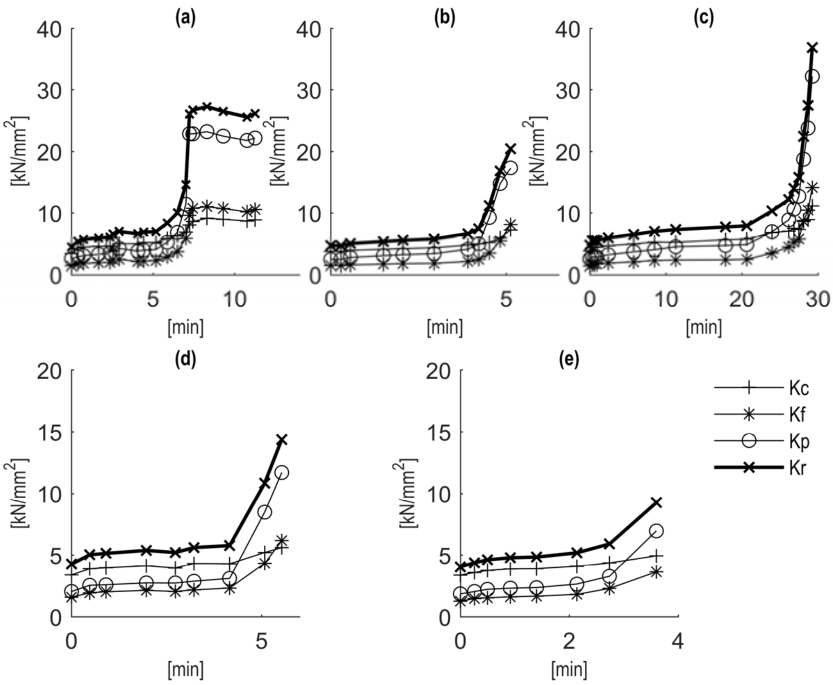


Figure 6. Specific force components vs machining time with the TS2000 tool supplied by Seco for different cutting conditions: (**a**) V = 50 m/min; f = 0.1 mm/rev; (**b**) V = 50 m/min; f = 0.15 mm/rev; and (**c**) V = 35 m/min; f = 0.1 mm/rev; (**d**) V = 50 m/min; f = 0.1 mm/rev; and (**e**) V = 50 m/min; f = 0.15 mm/rev. Depth of cut was 0.25mm for (**a**–**c**) and 0.5mm for (**d**,**e**).

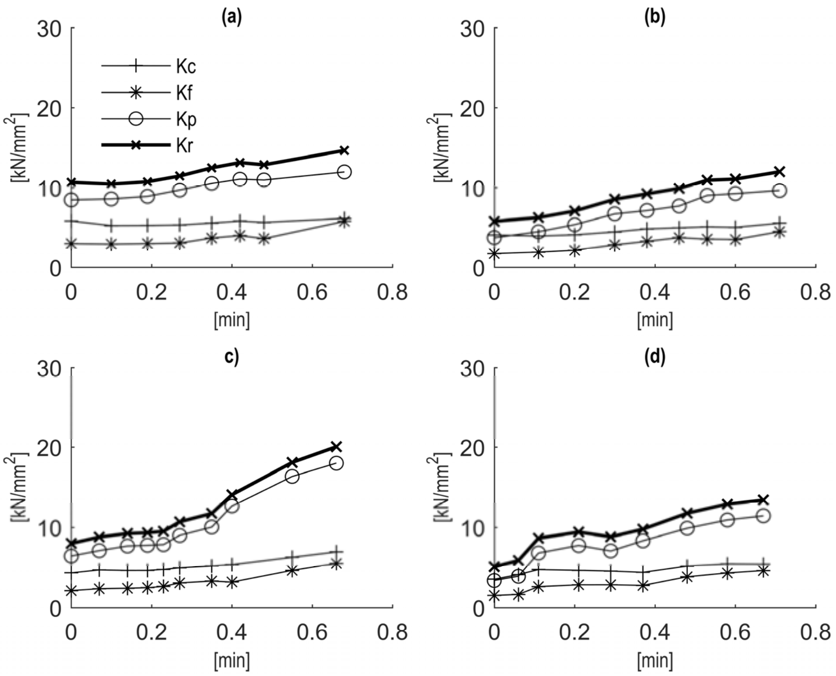


Figure 7. Specific force components vs machining time with the PCBN tool supplied by Seco for different cutting conditions. (**a**) V = 200 m/min; f = 0.15 mm/rev; d = 0.15 mm; (**b**) V = 200 m/min; f = 0.15 mm/rev; d = 0.25 mm; (**c**) V = 300 m/min; f = 0.15 mm/rev; d = 0.15 mm; (**d**) V = 300 m/min; f = 0.15 mm/rev; d = 0.25 mm.

3.2. Experimental Results: Tool Wear

As explained above, wear tests were carried out with carbide tools to establish a tool life reference point for dry finishing processes with this type of tool. In previous works by the authors [19], a systematic and broader analysis of tool wear was carried out for this type of process. In all conducted tests using carbide tools, chipping, flank wear, adhesion, and notching were found. At a cutting speed of 50 m/min, chipping and flank wear affects the entire active edge, but is more intense at the ends of the active edge, producing notch wear and high wear on the tool tip. Finally, breakage of size 0.4 mm or greater occurred on the tool tip, which led to the end of life (see Figure 8). In the test at a cutting speed of 35 m/min, the wear observed was very similar (chipping, flank wear, and adhesion). However, the wear progression was more homogeneous along the edge, without observing greater wear at the ends of the active edge. The end of life was produced by breaks of size 0.4 mm or greater in the central area of the edge.

Increments to any of the three cutting parameters (cutting speed, feed, or depth of pass) significantly accelerated wear mechanisms and diminished tool life (see Table 4).

In addition to the cutting time until the end of life, the amount of machined surface per cutting edge (S_{edge}), and the amount of machined surface per unit time ($S_{mach/t}$), have been considered in order to quantify the efficiency of the machining processes analyzed analogously as in [20]. Machined surface per unit time (mm^2/s) can be expressed by:

$$S_{mach/t} = V \cdot f \cdot 1000/60 \quad (1)$$

where V is the cutting speed (m/min) and f is the feed (mm), and achined surface per cutting edge (mm^2/edge) can be expressed by

$$S_{edge} = S_{mach/t} \cdot T/60 \quad (2)$$

where T is the tool life (min).

In particular, at cutting speeds of 35 m/min, long tool lives (29 min) and high machined surfaces per edge were obtained. The machined surface per unit of time was moderate due to the reduced cutting speeds required by this type of process. Therefore, the viability of dry finishing of Inconel 718 with carbide tools is confirmed.

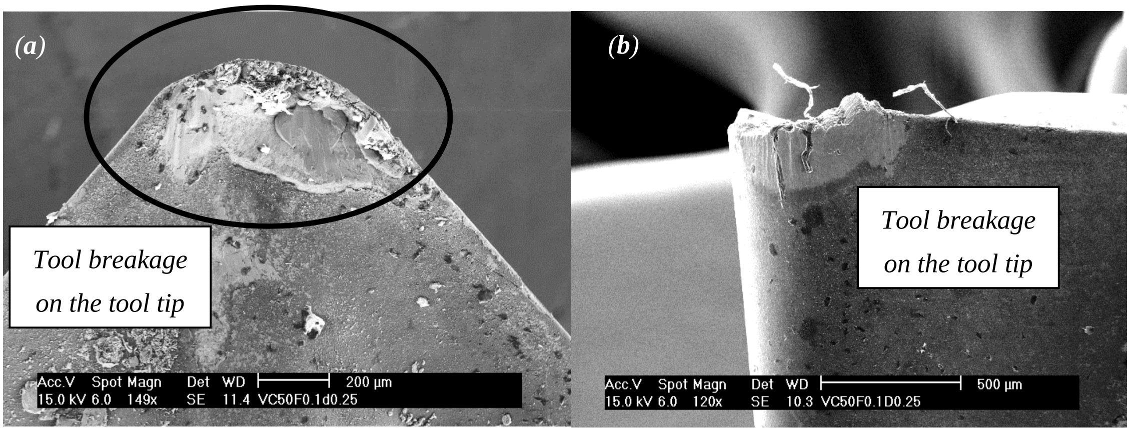


Figure 8. SEM images of the carbide tool supplied by Seco corresponding to the end of tool life with cutting speed 50 m/min, feed 0.1 mm and depth of cut 0.25 mm. (**a**) Tool breakage viewed from the rake surface; (**b**) Tool breakage viewed from the relief surface.

Table 4. Results of tool life and machined surface per cutting edge for all tests conducted.

Tool Material (Tool Grade)	Cutting Speed (m/min)	Feed (mm/rev)	Depth of Pass (mm)	Tool Life (min)	Machined Surface Per Unit Time (mm^2/s)	Machined Surface per Cutting Edge (mm^2/edge)
Carbide tool (TS2000, Seco)	35	0.1	0.25	28.7	58.33	100,450
	50	0.1	0.25	10.1	83.33	50,500
			0.5	6	83.33	30,000
		0.15	0.25	5.4	125	40,500
			0.5	3.9	125	29,250
PCBN (CBN170, Seco)	200	0.15	0.15	0.8	500	24,000
			0.25	0.8	500	24,000
			0.5	0.2	500	6000
	300	0.15	0.15	0.8	750	36,000
			0.25	0.7	750	31,500
			0.5	0.2	750	9000
PCBN (MB8025, Mitsubishi)	300	0.15	0.15	1.4	750	63,000
			0.25	0.5	750	22,500
			0.5	0.3	750	13,500
PCBN (KB5625, Kennametal)	300	0,15	0.15	0.7	750	31,500
			0.25	0.4	750	18,000
			0.5	0.3	750	13,500
PCBN (7015, Sandvik)	300	0,15	0.15	1.6	750	72,000
			0.25	0.7	750	31,500
			0.5	0.4	750	18,000
JP2 (NTK)	300	0,15	0.15	1.6	750	72,000
			0.25	0.7	750	31,500
			0.5	0.7	750	31,500

In all conducted tests using PCBN tools and JP2 grade, we found adhesion, chipping, notch, and crater wear. However, within these types of wear, notching (with a dimension of 0.4 mm or greater) most frequently leads to tool replacement.

For the reference Seco PCBN tool, two cutting speeds were tested (300 m/min and 200 m/min) at three levels of cutting depth (0.15, 0.25, and 0.5 mm), using a feed of 0.15 mm/rev. Wear evolution and tool life were similar for both cutting speeds, so the tool's efficiency in machined surface per cutting edge or machined surface per minute is greater at a cutting speed of 300 m/min. The increase of cutting speed increases the temperature of the tool, but only moderately affects wear due to PCBN's high resistance to high temperatures. Furthermore, as can be seen in Figure 4, cutting forces increase when cutting speed decreases. This means that the workpiece material is softer due to reaching higher temperatures at a cutting speed of 300 m/min; hence the stresses suffered by the tool are lower.

Finally, the wear and tool life obtained for the different manufacturers' tools considered in this study were comparatively analyzed at a cutting speed 300 m/min, three levels of cutting depth (0.15, 0.25, and 0.5 mm), and a feed of 0.15 mm/rev. The four PCBN tools (Seco, Mitsubishi, Kennametal and Sandvik) and the JP2 grade tool from NTK showed similar wear evolution.

For a depth of 0.5 mm, high heating of the tool and particularly high wear in the two zones on the edges of the chip (notch wear and wear at the tool tip) were observed. The notch wear reached values higher than 0.2 mm during the first seconds of machining. For cutting times between 0.2 and 0.7 min, notch wear reached values of 0.4 mm (value established as the end of life; see Figure 9a). Reducing the depth of pass to 0.25 mm without changing the remaining cutting conditions showed the same types of wear as in the tests at a depth of 0.5 mm, but with slightly lower growth. Usually, the predominant wear was notch wear, which reached a size of 0.4 mm or caused catastrophic edge breakage. Under these conditions, tool life was still very brief (between 0.4 and 0.8 min).

The best behavior found for all the tools were at a cutting speed of 300 m/min, a feed of 0.15 mm/rev, and a depth of cut of 0.15 mm. The dominant wear modes were chipping and adhesion wear, affecting the entire cutting edge; notch wear was not observed (see Figure 9b). Kennametal and Seco tools showed more tendency to chip due to their sharper cutting edge geometry and were hence less robust (they had a round honing of 25 μm). Thus, tool life for both tools was lower, never lasting longer than 0.8 min. The other tools (Mitsubishi's and Sandvik's PCBN tools and NTK's JP2 tool) reached their maximum tool lives between 1.4 and 1.6 min for the minimum depth of cut (0.15 mm).

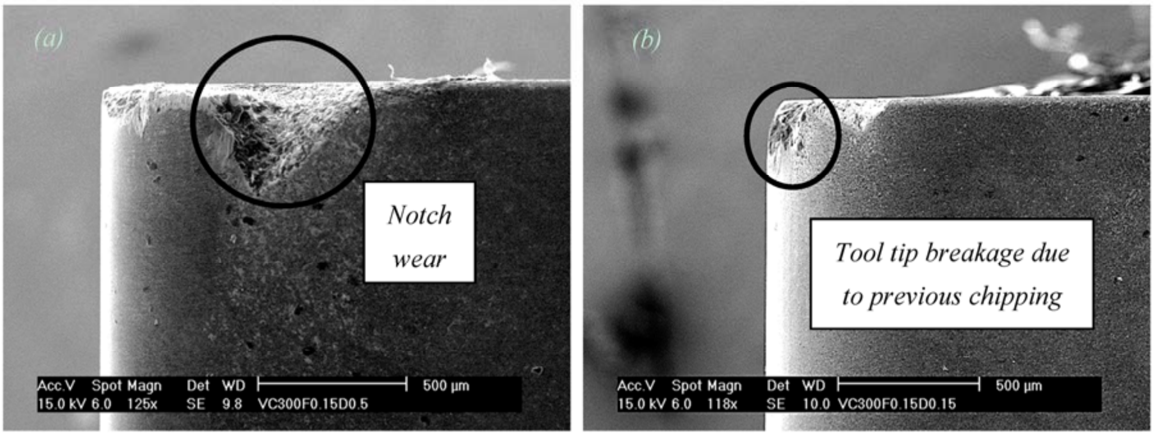


Figure 9. SEM images of the PCBN tool supplied by Seco corresponding to common types of wear found during the tests: (**a**) depth of cut 0.5 mm; (**b**) depth of cut 0.15 mm.

The obtained results indicate that tools with a more robust cutting edge (chamfer honing with a width of 50 μm or round honing with a radius of 35 μm) last somewhat longer than tools with a round honing of 25 μm.

Although the maximum tool life was only 1.6 min, the machined surface per edge was even higher than that obtained with carbide tools at 50 m/min, with the machined surface per unit time 6–13 times higher for the PCBN tool.

Despite apparently acceptable results with the NTK, Sandvik, and Mitsubishi tools, it must be considered that the uncertainty inherent in a machining process performed in a productive environment obliges machinists to replace their tools with a certain margin of safety, which prevents the application of tools with such limited theoretical lives. For comparative analysis of these types of tools it should also be kept in mind that the cost per edge of the PCBN tools can be up to 10 times higher than that of the carbide tools.

The study carried out is sufficiently broad and deep to establish that high speed finishing of Inconel 718 in a dry environment is not industrially viable, despite having confirmed that dry machining at conventional speeds with carbide tools is feasible. In general, the main problem of removing cutting fluids in machining processes is increased temperature in the cutting zone. PCBN inserts can tolerate cutting temperatures in excess of 1000 °C. Thus, PCBN inserts tend to behave better than carbide tools under dry conditions. However, the critical factor in eliminating cutting fluid when machining Inconel 718 is the greater chip formation instability that dominates the wear mechanisms related to tool fragility.

Our conclusion is justified based on the following observations, already described above:

(1) PCBN inserts have a much shorter life than carbide tools.
(2) PCBN tools with a more robust edge geometry (chamfered honing and round honing with a radius of 35 μm) have a longer duration than tools with round honing with a radius of 35 μm.
(3) An increase in depth of pass significantly reduces tool life.
(4) Increased cutting speed increases the temperature and improves the stability of the cut but has very little effect on the durability of PCBN tools.

Independently of tool manufacturer, we found a phenomenon associated with notch wear creation for PCBN tools. Notch wear leads (under some cutting conditions) to workpiece burr formation; subsequently, in posterior passes, the burr was eliminated by chipping, creating a secondary chip. Although the secondary chip is smaller than the primary chip, it may damage the tools in an unexpected way (see Figure 10b for an image of the secondary chip formation). The secondary chip gives information relative to the wear state of the tool. It does not appear when the tool is new (at the first instance of the tests; see Figure 10a). Information regarding chip morphology can be useful for numerical and analytical model validation.

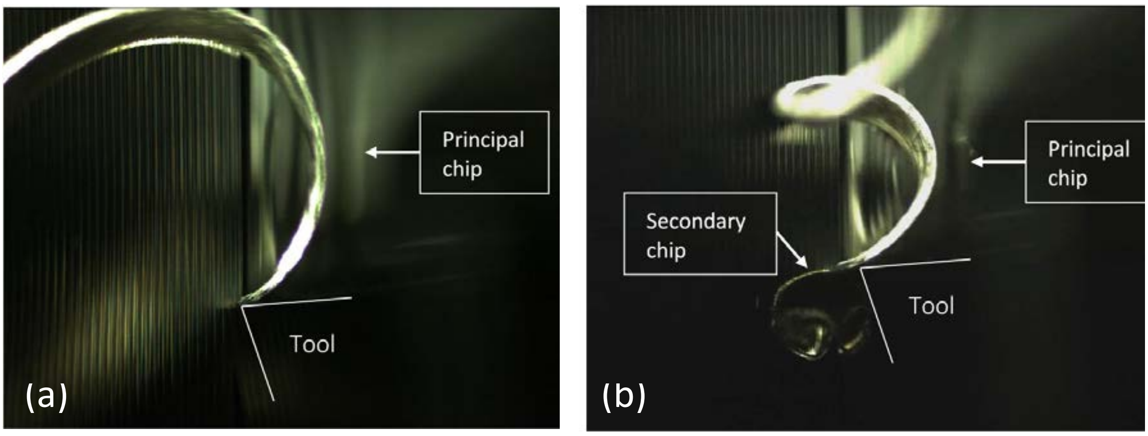


Figure 10. Picture taken with the high-speed camera during a test with the Seco PCBN tool at a cutting speed of 300 m/min, a feed 0.15 of mm/rev, and a depth of pass of 0.15 mm: (**a**) in the first instance of use; (**b**) after the presence of a significant notch in the tool.

3.3. Experimental Results: Surface Finish

The average roughness evolution in the machined surface with the wear state of the tool was recorded for each test. Figure 11 shows the average roughness corresponding to the first machining instance (using an unworn tool) and to the worn tool (at the end of life). These values represent the maximum Ra obtained after performing measurements on the five areas of the machined surface (variations were lower than 4% per studied condition). The values obtained for the tests with PCBN tools at a cutting depth of 0.5 mm have not been included due to high tool wear which makes it impossible to establish the values corresponding to an unworn tool.

During the first instance (using an unworn tool), good surface finishes were obtained under all the conditions tested. In the tests with the carbide tool, two feeds were used. In tests with a feed of 0.1 mm/rev, values of Ra ranged from 0.7 µm to 0.9 µm, and in tests with a feed of 0.15 mm/rev, values of Ra were between 0.8–1.3 µm. Obtained roughnesses for the PCBN and JP2 tools without wear (feed 0.15 mm/rev) were of the same order of magnitude, between 0.8 and 1.3 µm. The depth of pass and cutting speed did not have a significant effect on the surface finish obtained using a new tool.

Surface finish evolution during the tool life was very variable and accorded with the dominant wear characteristic. If the end of life was due to notching, with low wear in the rest of the cutting edge, roughness was stable, reaching the same values as with an unworn tool. If wear was localized on the tool tip or along the cutting edge, roughness was greater than 2 µm. Remarkably, the highest roughness was found for worn Seco PCBN tools tested at a cutting speed of 200 m/min. However, all worn tools tested at a cutting speed of 300 m/min have moderate variation of Ra.

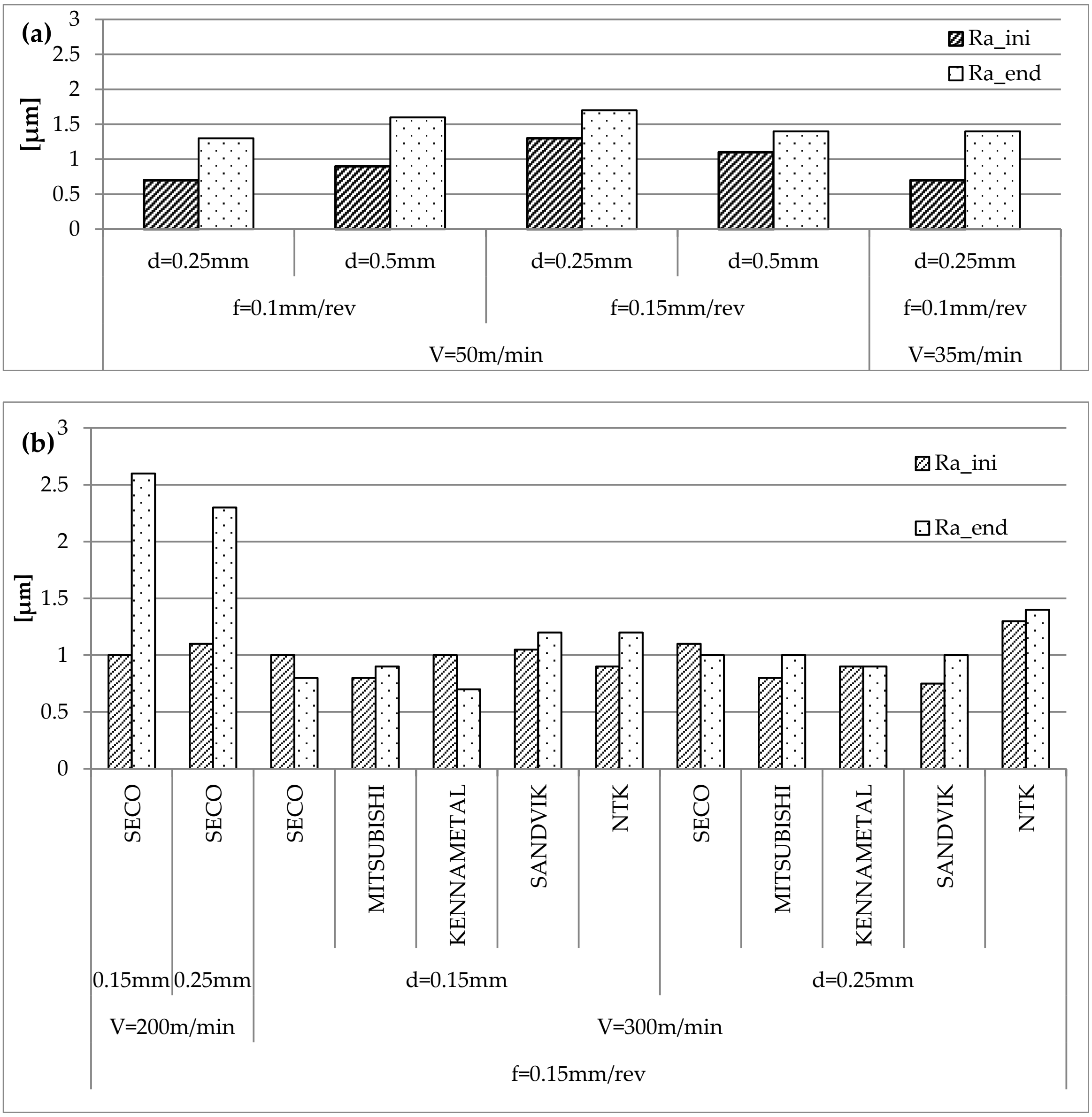


Figure 11. Average roughness (Ra) measured at the beginning of the test (Ra_ini) and at the end of tool life (Ra_end) in turning tests with: (**a**) Seco tool of TS2000 grade and (**b**) PCBN and JP2 grade cutting tools.

4. Conclusions

In this study, PCBN tools from four different tool manufacturers (Seco, Mitsubishi, Sandvik, and Kennametal) and a JP2 grade tool (NTK) were used for finish turning of Inconel 718 at high cutting speeds under dry conditions. Further machining tests with coated carbide tools were also carried out, allowing comparative analysis between high- and conventional-speed dry machining of Inconel 718. Carbide tool life reached up to 29 min in tests with lower cutting speeds, feed rates, and cutting depth. Therefore, the viability of dry finishing of Inconel 718 with carbide tools was confirmed. Coated carbide tools are affected negatively with increased the cutting speed. There was an increase of almost 200% in the tool life for this kind of tool when the cutting speed changed from 50 m/min to 35 min/min.

For all conducted tests using PCBN tools and JP2 tools, adhesion, chipping, notching, and crater wear were found. However, of these wear types, notch wear most frequently lead to tool replacement. Throughout all cutting conditions employed, tool lives were shorter than 2 min. It is concluded that it dry high-speed finishing of Inconel 718 is not industrially viable. Greater chip formation instability produced by the lack of cutting fluid promotes wear mechanisms related to the tool fragility.

Shorter tool life was obtained for tools with weaker cutting edge geometries (Seco and Kennametal tools, with round honing: radius of 25 μm). In general, increased cutting depth significantly reduced tool life; however, feed had less effect on PCBN tool life. Longer tool life was obtained with the smallest depth of pass (0.15 mm) for Sanvik and Mitsubishi PCBN tools and the JP2 grade tool from NTK. These three tools have different cutting edge geometries and coatings; however, they showed similar wear resistance. Specific cutting forces for these three tools were observed to be slightly superior to those of the NTK tool, due to its more negative cutting edge (chamfer honing, with a honing width of 50 μm, and a honing angle of $-20°$). Hence, the best performances when machine finishing Inconel 718 under dry conditions were obtained for round-honed cutting edges with a radius of 35 μm (the Sandvik tool) and chamfer-honed edges with a honing width of 50 μm and a honing angle of $-15°$ (the Mitsubishi tool).

In tests with carbide tools, between 1 and 3 min before the end of tool life, the cutting forces increased sharply, especially the back force component. It should be noted that this sudden increase in forces does not correspond to significant growth in the geometrical wear of the tool, which increases very gradually up to the end of life. Therefore, back force monitoring could allow the control of tool wear in industrial machining applications.

In reference to surface integrity, good surface finishes were obtained for all conditions tested during the first instance of use (with an unworn tool). Depth of pass and cutting speed do not have a significant effect on the surface finish obtained using a new tool. The surface finish evolution did show very variable behavior according to the dominant type of wear. If the dominant wear during tool life is notching, with low wear on the rest of the cutting edge, average machined roughness is not affected until the end of life. If wear is localized on the tool tip or along the cutting edge (as in the tests with the CBN170 grade tool at V = 300 m/min), roughness is greater than 2 μm.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CBN	cubic boron nitride
d	depth of pass
f	feed rate
Fc	Cutting force
Ff	Feed force
Fp	Back force
Fr	Resultant force
Kc	Specific cutting force
Kf	Specific feed force
Kp	Specific back force
Kr	Specific resultant force
PCBN	Polycrystalline cubic boron nitride
SEM	Scanning electron microscopy
Smach/t	Machined surfaced per unit time
Sedge	Machined surface per cutting edge
T	Tool life
V	Cutting speed

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