INCREASING TOOL LIFE THROUGH ADJUSTMENT OF CUTTING EDGE AND TOOLPATH DURING MILLING OF INCONEL 718

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This paper focuses on analysis of tool life during milling of nickel alloy Inconel 718. Several modifications of one type of carbide tool with different cutting edge finish adjustments (lapping, drag finishing) were proposed for milling of Inconel 718. These finish adjustments significantly influence cutting edge properties (hardness, radius value, etc.). The toolpath geometry setup has a great influence on chip formation and tool load characteristics during milling strategies. The milling tests were performed by using the cutting tools with several adjustments of cutting edge in combination with the toolpath geometry setup. The paper therefore presents the analysis that tool life can be significantly increased through proper finish adjustment of cutting edge microgeometry and proper toolpath setup.

KEYWORDS

Tool, Cutting edge, Toolpath, Nickel alloy, Milling, Tool life

1 INTRODUCTION

Machining workpieces made of difficult-to-cut materials is a demanding process, not only in terms of setting the technological conditions, tool and workpiece clamping, but also because the tool has to withstand very demanding conditions during machining. These are, in particular, high temperatures and cutting forces during machining. Therefore, it is very important to have a suitable tool that renders the workpiece machinable while also making the machining technology economical, i.e. effective. This requires knowledge of tool life and productivity. One alloy that is categorized as a difficult-to-cut material is Inconel 718. This alloy is one of the most widely used difficult-to-cut materials, e.g. in the automotive, power and aerospace industries.

Previous investigations have shown that cutting edge adjustments with brushing, blasting or laser machining can improve tool life for cemented carbide inserts or conventional milling and drilling tools [Denkena 2014], [Denkena 2012]. The results presented by Uhlmann et al. [Uhlmann 2016] show general improved performance of micro milling tools with adjusted cutting edges using the immersed tumbling process.

Cutting edge microgeometries can be produced by means of brushing, drag finishing or laser ablation techniques with different effects on the radius and form [Aurich 2011]. The authors also emphasize the specific influence of a different cutting tool microgeometry characterization achieved by applying cutting edge adjustment technology to machining processes. The principles of the material removal mechanism during drag finishing are described in detail by Lv et al. [Lv 2022]. Four types of abrasives are used to analyse the effect on the material removal capability and the achievement of the cutting edge radius value. The highest cutting edge radius value is achieved when HSO 1/100 abrasive is used.

Nomeclature	
a_e	radial depth of cut [mm]
a_p	axial depth of cut [mm]
v_c	cutting speed [m·min^{-1}]
f_z	feed per tooth [mm]
z	number of tooths [-]
D	tool diameter [mm]
D_m	dimension of the machined slot [mm]
D_{vf}	diameter of the trochoidal section of toolpath [mm]
n	spindle speed [min^{-1}]
i_{troch}	number of circular sections of trochoidal toolpath [-]
v_f	feed rate [mm·min^{-1}]
v_{fm}	recalculated feed rate for trochoidal toolpaths [mm·min^{-1}]
MRR_{conv}	material removal rate for conventional milling [mm^3·min^{-1}]
MRR_{itroch}	material removal rate per one trochoidal section of toolpath [mm^3·min^{-1}]

The study performed by Zetek et al. [Zetek 2013] shows that the greater the resulting cutting radius, the longer the tool life of the carbide tool during machining of Inconel. The author deals with only one of the cutting edge adjustment technologies available. Effect of cutting edge preparation on the tool performance has been analysed also for coated tools [Bouzakis 2014].

Ma et al. [Ma 2019] analyze the effects on tool wear and tool life during high-speed machining of Inconel 718. Several tools with different tool cutting edge geometries are used in the machining test where only the geometry parameters (Rake angle, Relief angle, Helix angle) are varied. It was concluded, that the smaller the rake angle the higher strength. Another finding is that the higher the relief angle the higher the tool life is. Using of higher helix angle than 30° will then reduce the tool life significantly.

Aramesh et al. [Aramesh 2018] proposed a novel metod of treatment of the tools for milling of Inconel 718. They used a new Al-Si layer which is applied on the cutting edge of the tool by pre-machining proces. The new tool is used to mill Al-Si workpiece for a less than two seconds before it is used to mill the workpiece from Inconel. This treatment brings reduced friction between the tool and the workpiece and leads to enhanced tool life.

Carbide tool machinability performance is increased by selection of appropriate cutting strategies, cooling systems and determination of optimum cutting parameters for maximum tool life. The machinability performance of these superalloys improves considerably, as reflected in [Motorcu 2013]. Krain et al. [Krain 2007] show recommended cutting conditions for carbide tool machining that is productive and also achieves the best tool life.

Peterka et al. [Peterka 2020] investigated the time-dependent increase of the cutting edge radius value during drag finishing of a carbide milling tool. The tools were first sharpened and then drag finished and the cutting edge radius value was measured at regular time intervals. It was found that the fastest increase in the cutting edge radius value occurs in the first ten minutes of the drag finishing process, during which a radius of 15 μm was reached. Thereafter, the increase of radius value is slower and, depending on the granulate used for drag finishing, does not exceed a certain radius limit. A radius value of 30 μm was reached after 100 min. Mrkvica et al. [Mrkvica 2017] show that not only the selected cutting conditions, but especially the geometry of the tool cutting edge have a significant influence on the tool wear during machining of Inconel 718. The tool life test was carried out using three types of milling tool indexable inserts. The effective cutting conditions for carbide tools has been also analysed for turning of Inconel 718 [Alagan 2019].

Adaptive toolpaths are often used in CAM (Computer Aided Manufacturing) systems for machining difficult-to-cut materials, which ensure that the constant engagement angle between the tool and the material is maintained during machining. Similarly designed toolpaths should be used for tool testing. The starting point for similar types of toolpaths are trochoidal toolpaths, which can be parameterized. A study that offered epicycloid toolpaths as an alternative toolpath formation to trochoidal toolpaths can be seen in [Salehi 2016]. It shows that it is possible to reduce machining time while increasing cutting forces using epicycloid toolpaths.

It was also proofed that it is necessary to recalculate the feed rate to achieve a constant feed per tooth. The method of achieving constant feed per tooth at contact point using feed rate control in 2D toolpaths is presented by Vavruska et al. [Vavruska 2022]. The recalculation of feed rate to maintain constant feed per tooth brings smoothing of cutting forces during milling when using curved toolpaths.

No analyses were found of how the different cutting edge adjustments in combination with toolpath type impact tool life and productivity. Therefore, this paper focuses on the design of a tool with various technological cutting edge modifications, which, in combination with two types of toolpaths, is subjected to tool life testing during machining of Inconel 718.

2 PROPOSED TOOL DESIGN AND CUTTING EDGE ADJUSTMENTS

Initially, the macro-geometry of the tool for milling Inconel 718 was designed based on the following parameters: shank diameter 10 mm, cutting diameter D = 10 mm, corner radius 0.5 mm, blade length 15 mm, tool length 65 mm, right helix with 45°, uncoated. The tool can be seen in Fig. 1. To adjust the cutting edge microgeometry, the following cutting edge finishing methods were chosen.

Figure 1. Tool proposed for milling of Inconel

The basic version of the tool was produced standardly without any subsequent finishing of cutting edge microgeometry and is labelled R-10216-0. To create other tool types, the cutting edge microgeometry was modified using different finishing methods to increase tool performance. For the tool labelled R-10216-1, a drag finishing strategy was used to adjust the cutting edge. Lapping was applied to adjust the cutting edge of the tool labelled R-10216-2. For the cutting edge adjustment of tool R-10216-3, both of these finishing methods were combined. An Alicona Infinite Focus optical microscope was used to measure the cutting edge radius after final surface adjustment. The type of adjustment and the final radius of each tool version are summarized in Tab. 1.

Table 1. Tool versions with different cutting edge adjustments

Tool label	Cutting edge adjustment	Cutting edge radius (μm)
R-10216-0	With no cutting edge adjustment	1.9
R-10216-1	Drag finishing	2.4
R-10216-2	Lapping	2.6
R-10216-3	Drag finishing and lapping	5.5

3 TOOL LIFE ANALYSIS

For tool testing, the conventional roughing strategy was set as well as the trochoidal machining strategy, the advanced machining strategy commonly used in groove and pocket machining and in the machining of difficult-to-cut materials.

3.1 *Toolpaths settings*

When testing tools with trochoidal machining strategies, the tool performs a circular motion and alternates between the area where the tool is in engagement with the material and the area where the tool is outside of the material. Thus, it is not as easy to measure tool time in the cut as it is with conventional toolpaths and a subsequent comparison of tool life between these two strategies is not meaningful. To make the measurement comparable to conventional machining, the material removal rate (MRR) was determined as a reference. For roughing using the conventional method, the MRR_{conv} was calculated from the cutting conditions using formula (1). Next, the trochoidal strategy must be arranged to get the same MRR as for conventional toolpaths ($MRR_{troch} = MRR_{conv}$). The material removal rate for the trochoidal strategy can be calculated as $MRR_{troch} = MRR_{itroch} \cdot i_{troch}$ where MRR_{itroch} is the material removal rate per trochoidal revolution and i_{troch} is the number of trochoidal toolpath sections (number of „circular“ sections of toolpath).

$$MRR_{conv} = a_p \cdot a_e \cdot \frac{1000 \cdot v_c}{\pi \cdot D} \cdot z \cdot f_z \quad [\mathrm{mm^3 \cdot min^{-1}}] \qquad (1)$$

$$i_{troch} = \frac{MRR_{conv}}{MRR_{itroch}} \quad [-] \qquad (2)$$

Trochoidal machining strategy was created to match conventional strategy parameters and thus ensure comparability of the results (Fig. 2).

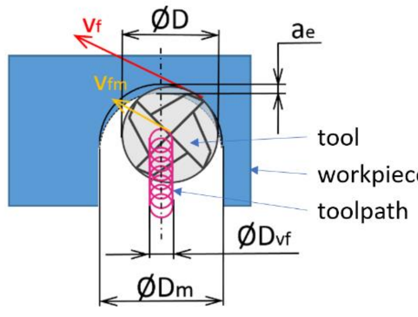

Figure 2. Trochoidal strategy parameters

The axial depth of cut a_p was set equal to 4 mm. The radial depth of cut a_e = 0.5 mm was used like a step of trochoidal surgery. To maintain the required feed per tooth f_z, the programmed feed rate v_f needs to be recalculated. By default, the CAM program refers to the feed rate at the tool center, so for trochoidal machining, the circumference of the tool moves at a greater feed rate than the programmed feed rate due to the trochoidal motion. The actual feed rate for trochoidal milling is thus the peripheral speed, and therefore the programmed feed rate for trochoidal machining (v_{fm}) must be reduced in proportion to the ratio of the diameter of the „circular" section of toolpath D_{vf} to the dimension of the machined slot D_m, see formula (3).

$$v_{fm} = \frac{D_{vf}}{D_m} \cdot n \cdot z \cdot f_z \quad [\text{mm}\cdot\text{min}^{-1}] \qquad (3)$$

To save on tool life testing costs, a cylindrical blank was bought which first had to be modified by milling to allow the maximum volume of material to be defined for testing. Then the conventional toolpath and trochoidal toolpath have been proposed for testing. The proposed trochoidal toolpath can be seen in Fig. 3. The setup of clamped workpiece on the machine tool prepared for milling is shown in the Fig. 4.

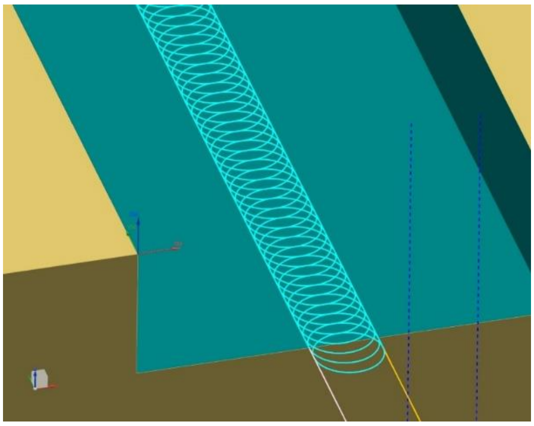

Figure 3. Proposed trochoidal toolpath for milling

Figure 4. Clamped workpiece on the machine tool prepared for milling

3.2 Tool life measurement

The tool life was measured during the two proposed machining strategies mentioned above. A Tajmac ZPS MCFV 5050 LN 3-axis milling machine tool with Sinumerik 840D control was chosen for manufacturing. This machine tool is equipped with a spindle with a maximum spindle speed of 15000 RPM and ISO 40 tool interface. The measurement of tool wear respecting the standard ISO 3685 was performed by using a Laboratory imaging optical microscope (Fig. 5), which consists of Macro-lens Navitar 12x zoom with front cover Navitar 12x - 2.0x, colour camera 33UX250 2/3" and control unit MW Tango 3 Desktop.

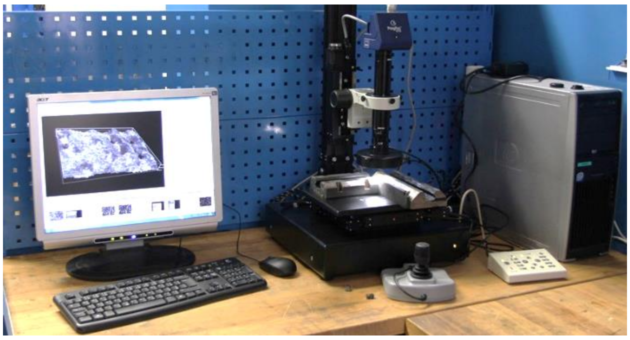

Figure 5. Laboratory imaging optical microscope

The comparison was made using the maximal value of the intermediate wear on flank face ($VB_{b\,max}$). The average value of $VB_{b\,max}$ was calculated of all cutting edges with the same adjustment. The limit value of the wear for tool life analysis was assessed on the basis of previous experience and deal with the tool producer ($VB_{b\,max\,lim}$ = 300 μm). The cutting conditions used for machining were: v_c = 40 m.min^{-1}, f_z = 0.06 mm, a_e = 0.5 mm and a_p = 4 mm. The average measured values of flank wear when conventional milling can be seen in the Tab. 2. It is apparent from the measured wear values that the dominant increase in wear is at two thirds of the depth of cut (Fig. 6) after milling using conventional strategies. This is typical wear during machining of Inconel 718.

Table 2. Average flank face wear $VB_{b\,max}$ when conventional milling

Time T [min]	8	16	24	32	36	40	44	48
Tool	average $VB_{b\,MAX}$ [μm]							
R-10216-0	60.4	93.9	151.5	182.5	243.5	374		
R-10216-1	48.1	107.1	217.6	329.6				
R-10216-2	50.8	83.8	148.9	177.6	227.9	270.5	287.9	305.5
R-10216-3	50.5	81.6	136.3	238.1	320			

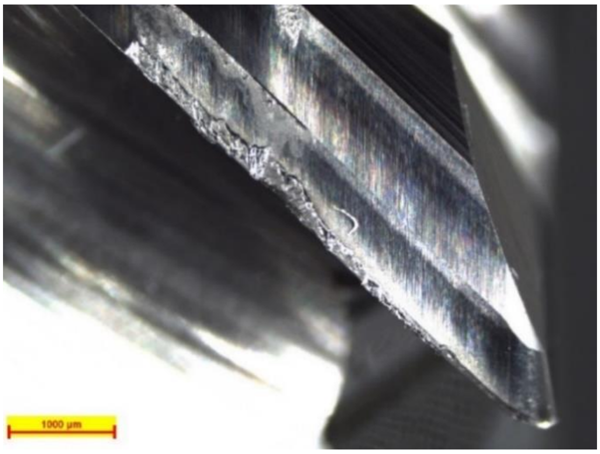

Figure 6. Typical tool wear during conventional roughing of Inconel 718

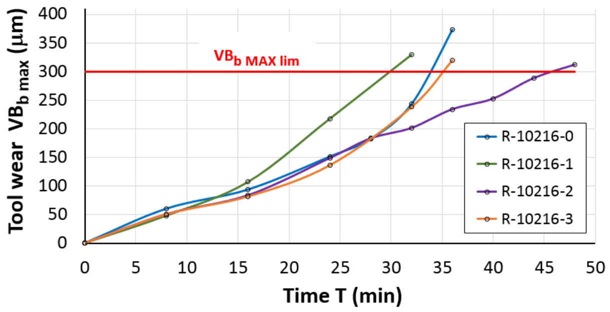

Figure 7. Graphical comparison of average $VB_{b\ max}$ wear characteristics for all tested tools when Inconel 718 conventional milling with cutting conditions: v_c = 40 m.min^{-1}, f_z =0.06 mm, a_e = 0.5 mm, a_p = 4mm

The tool life analysis for conventional strategies can be seen in Fig. 7. It is obvious that the longest tool life of conventional roughing milling of Inconel 718 was achieved by cutting the edge with lapping (R-10216-2). This cutting edge adjustment provides a 35% longer tool life than without an adjusted cutting edge (R-10216-0). Lapping reduces the friction between the tool and the material to be machined. This has the effect of extending tool life during conventional roughing. On the other hand, the shortest tool life resulted from milling with the drag-finished cutting edge (R-10216-1). With this cutting edge, the tool life is 8% less durable on average than for the tool with no adjustment. From the point of view of conventional roughing of Inconel 718, it is therefore recommended to use tools with a lapped cutting edge.

Table 3. Average flank face wear $VB_{b\ max}$ when trochoidal milling

Time T [min]	15	30	45	60	75	80	85	90	92
Tool	average $VB_{b\ MAX}$ [μm]								
R-10216-0	22.5	37.8	59.5	62.5	218.3	724.8			
R-10216-1	23.8	37.8	49.5	64	90.3	144	563.3		
R-10216-2	22.25	40	60.5	63.3	68.3	218.5	432.7		
R-10216-3	19	41.9	58.9	75.4	96.5	112.6	145.2	238.3	359

Figure 8. Typical tool wear during trochoidal milling of Inconel 718

The average measured values of flank wear when trochoidal milling can be seen in the Tab. 2. The measured values show that the dominant wear in trochoidal milling of Inconel 718 is halfway through the depth of cut (Fig. 8).

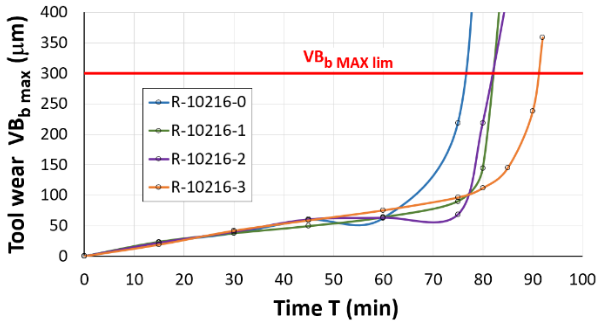

Figure 9. Graphical comparison of average $VB_{b\ max}$ wear characteristics for all tested tools when Inconel 718 trochoidal milling with cutting conditions: v_c = 40 m.min^{-1}, f_z = 0.06 mm, a_e = 0.5 mm, a_p = 4mm

The increase in wear demonstrates that the wear increases smoothly and the avalanche wear of the cutting edge occurs at the end of the tool life (Fig. 9).

From the point of view of comparing the specific tool edge adjustments, the cutting edge is exposed to a high load at low chip thicknesses. For this reason, the tool with no adjustment (R-10216-0), which has the sharpest cutting edge geometry, has the shortest tool life. The sharp geometry of this tool is not able to withstand high cutting loads at low chip thicknesses and wears out more quickly. The longest tool life during trochoidal milling of Inconel 718 was achieved with the cutting edge adjusted by combination of drag finishing and lapping (R-10216-3). This adjustment provides a 20% longer tool life than the cutting edge with no adjustment (R-10216-0). This cutting edge has the largest cutting radius, and this results in a higher cutting edge resistance to varying chip thicknesses depending on the trochoid removal. In terms of trochoidal roughing of Inconel 718, the R-10216-3 cutting edge tooling tool can therefore be recommended.

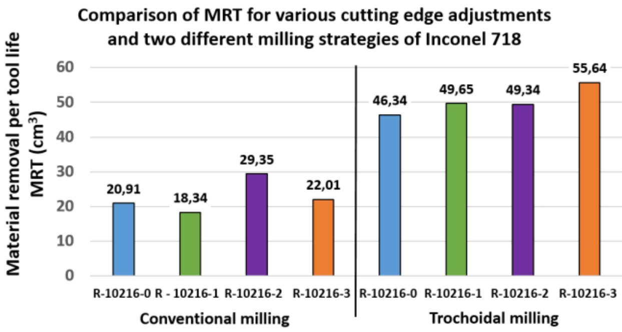

Figure 10. Comparison of volume of material removed per tool life (MRT) for various cutting edge adjustments and two different milling strategies

The comparison of conventional milling with trochoidal milling is highly noteworthy (Fig. 10). The two types of milling were compared using a calculation of volume of material removed per tool life (MRT). It can be claimed that during trochoidal machining, tools cut an average of 25 cm^3 more material off per their tool life than in the case of conventional machining. Therefore, in the view of this comparison, it is preferable to use the trochoidal machining strategy for roughing Inconel 718 as extensively as possible in terms of tool life and the material removed per tool life (MRT).

3.3 *Application opportunity*

Typical parts where this knowledge can be applied are parts from aerospace and automotive industry, often made from difficult-to-cut materials. Example of a stator blade wheel as a one of the parts where a roughing strategy, i.e. a suitable combination of tool and milling strategy, can be applied is seen in Fig. 11.

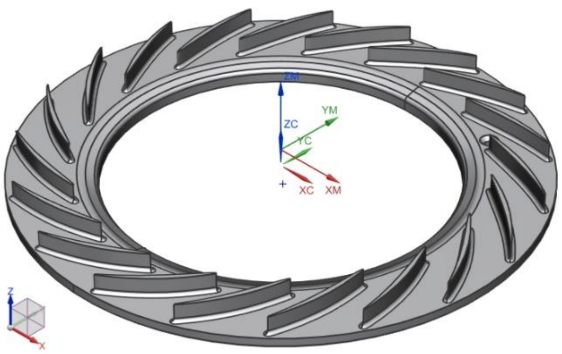

Figure 11. Example of a stator blade wheel

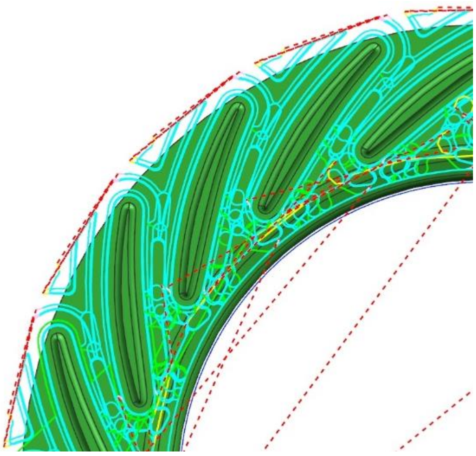

Figure 12. Example of a conventional roughing strategy

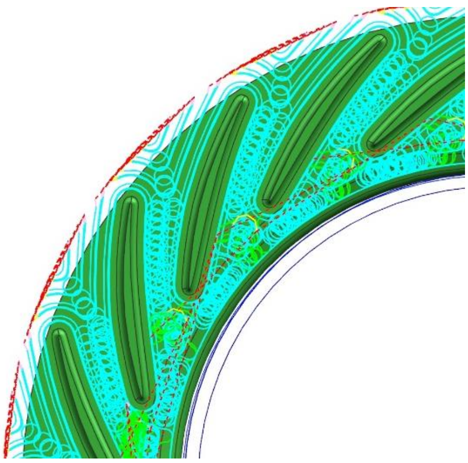

Figure 13. Example of a trochoidal roughing strategy

A comparison of the conventional roughing strategy and the trochoidal strategy for milling the space between the blades is shown in Fig. 12 and Fig. 13. As can be seen, the trochoidal toolpath (Fig. 13) is longer, than the conventional one (Fig. 12). On the other hand, the trochoidal toolpath can be often performed in single level (thanks to the controlled value of radial depth of cut at inner corners), contrary to the conventional one, that often needs to be performed at several levels (thanks to the non-controlled value of radial depth of cut at inner corners).

Based on the comparison of tool life with different cutting edge modifications, the cost of the machining strategy in terms of tool consumption can be estimated. Based on the length of the toolpath and the set feed rate, the time consumption can also be evaluated and therefore the costs from the machine tool can be estimated based on the machine cost per hour. Based on the knowledge and evaluation of both of these costs, i.e. tooling and machine side, the appropriate solution can be selected for the specific machining case.

4 CONCLUSIONS

Trochoidal or adaptive strategies are a progressive type of strategy for roughing of parts made of difficult-to-cut materials. It was analysed that specific milling strategy needs specific adjustment of cutting edge to achieve the best tool life and productivity. The performed milling tests using four different versions of cutting edge adjustments of solid carbide tool provides these main conclusions:

- the best cutting edge adjustment from the four tested versions is lapping in terms of tool life during conventional roughing of parts made from Inconel 718, which achieved a 35% longer tool life compared to the tool without an adjusted cutting edge;

- the shortest tool life resulted by using the tool version with a drag-finished cutting edge when conventional roughing (by 8% less tool life compared to the tool with no adjustment);

- the longest tool life during trochoidal milling was achieved with a combined cutting edge adjustment (drag finishing and lapping). This adjustment provides a 20% longer tool life than the cutting edge with no adjustment. The cutting edge with this adjustment has the largest cutting radius and this results in a higher cutting edge resistance to varying chip thickness;

- the shortest tool life when trochoidal milling was achieved by using the tool with no adjustment of cutting edge.

A comparison of tool life between conventional roughing and trochoidal roughing strategies was performed on the volume of material removed per tool life. The volume of removed material is higher using trochoidal strategies. The tools cut by an average of 25 cm^3 more material off per their tool life during trochoidal milling than in the case of conventional milling The highest amount of material was obtained during trochoidal machining with the combined drag finishing and lapping cutting edge adjustment.

These conclusions point to the evident advantages of the described milling tool versions with respect to the given technological strategy. Based on these conclusions, it is therefore possible to prepare an adequate tool and cutting edge adjustment for a given manufacturing strategy and make it more productive in regard to the tool.

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