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On the profile change of conical skiving tools after re-sharpening

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Abstract

Gear skiving is a productive process for manufacturing internal gears that has been spreading among companies in recent years. In gear skiving, conical shaped tools are used to avoid interference during machining. However, due to the conical shape, both the tool tip diameter and the tool profile change after re-sharpening, leading to a change in cutting performances during the tool service life. This paper aims at investigating the impact of the profile change on the process through simulations and experiments. Sensitive tools to profile change are identified and a strategy to reduce the difference in cutting performances is proposed.

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1. Introduction

Due to the environmental emergency, the current vehicle market is demanding an ever-increasing number of internal gears needed in most planetary gearboxes of electric vehicles. Gear skiving is more productive than shaping and more flexible than broaching, which are the most competing processes for manufacturing internal gears. Consequently, gear skiving has spread among gear companies in the last decade.

Since the tool plays a central role in the process, investigation on tool design constitutes a major topic in gear skiving [1]. Skiving tools can be distinguished based on their external shape which can be either conical or cylindrical. In conical tools, a constructive clearance angle is machined on the external surface of the tool to avoid interference with the gear machined. On the other hand, cylindrical tools have no constructive clearance angle. Thus, to avoid interference, the tool must either be tilted during the operation, requiring an extra degree of freedom to the machine tool, or it must be operated in an eccentric position with respect to the gear [2].

To date, several contributions have been made related to both conical [3–6] and cylindrical [7–9] tool designs. Among the main advantages that cylindrical tools over conical tools offer, is that the tool profile does not change during the tool service life due to re-sharpening. Indeed, in order to obtain the clearance angle at the tip, conical tools are designed in such a way that the profile shift coefficient decreases with re-sharpening [6]. Hence, a change of the tool profile shape during the tool service life is unavoidable, with the related risk of impairing cutting performances.

However, in practice, due to the added complexity in the machine tool architecture that the use of cylindrical tools entails, not all machine tools on the market today can use cylindrical tools, while virtually all can use the conical ones. Therefore, despite their inherent drawback, conical tools are the most used to date for gear skiving and their profile change represents a widespread issue in industrial practice.

Although the problem has been documented in the literature [2,9], to the best Authors' knowledge, it has not yet been adequately addressed. Hence this study aims at investigating in

which cases the re-sharpening of conical skiving tools can lead to significant changes of the tool profile and to which extent such changes can affect the tool performances.

The paper is structured as follows. Section 2 identifies the geometric parameters that characterize conical tools which are most sensitive to the change of cutting profile after re-sharpening. Sections 3 and 4 analyse, through simulations and experiments of two case studies, to which extent the cutting performance, assessed in terms of tool wear, are affected by the change of cutting profile. A process strategy to homogenise the cutting performance is presented in Section 5, while discussions and conclusions are drawn in the last two Sections.

2. Geometric parameters of the most sensitive tools to cutting profile change due to re-sharpening

The procedure for the calculation of the cutting profile of a skiving tool is briefly summarized in the next Paragraph in order to facilitate the understanding of the following. The reader might also refer to [6,7,10]. For the sake of simplicity, in the following discussion, reference is made to the case of a conical tool operating in a centred position with respect to the workpiece, but the results also apply to conical tools operating in an eccentric position.

2.1. Calculation of the cutting profile

The cutting profile of a skiving tool is calculated as the intersection of the conjugate surface of the gear to be cut, often referred to as the generating gear, with the tool rake plane. The generating gear depends on the geometry of the gear gap to be machined, and on the relative kinematics of the skiving process during the last pass, i.e. on the cross-axis angle Σ , the gear ratio k , and the centre distance a . The last depends on the gear root radius r_{rG} and on the tool tip radius r_{tT} and can be defined by the following equation:

$$a = r_{rG} + \varepsilon \cdot r_{tT} \quad (1)$$

where $\varepsilon = -1$ for internal gears and $\varepsilon = 1$ for external gears. In conical tools the tool tip radius decreases between the tool start of life (SOL) and the tool end of life (EOL) with re-sharpening. The relationship between tool tip radius and the re-sharpening depth can be of several types, in this study it is assumed to be linear. Referring to Fig. 1, by dividing the tool usable height h into n -parts corresponding to the n -re-sharpening steps h_i that are met during the tool service life, the value of the tool tip radius at the i -th re-sharpening step may be written as:

$$r_{iT_i} = r_{tT0} - \sum_{i=1}^n h_i \cdot \tan(\alpha_c) \quad (2)$$

where r_{tT0} is the nominal tool tip radius of the tool, namely when the tool is at the SOL, and α_c is the clearance angle (Fig. 1). By considering both Eqs. (1) and (2) it can be concluded that each re-sharpening step yields a different centre distance a , which translates into a slight variation of the relative kinematics and hence of the generating gear.

Therefore, in order to define a conical skiving tool, n -sections are taken on the rake plane, one for each

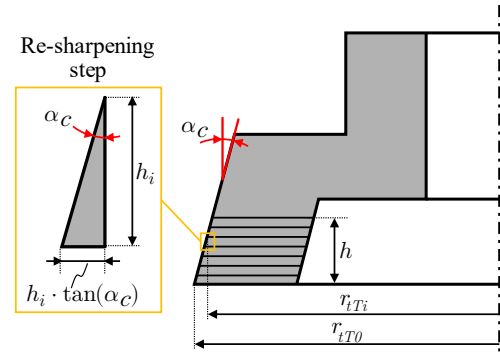


Fig. 1. Re-sharpening of a conical tool.

re-sharpening step and its corresponding generating gear, resulting in n -different tool cutting profiles.

By placing each of the n -profiles so obtained at their own re-sharpening depth while considering the tool lead, the flanks of the skiving tool are obtained.

2.2. The profile shift coefficient

From the theory of gearing [11], the profile shift coefficient x of a gear profile generated by a rack can be defined with the following equation:

$$x = \frac{e}{m_n} \quad (3)$$

where e is the displacement of the rack relative to the pitch diameter of the generated gear profile and m_n is the normal module. Considering the method for the calculation of the skiving tool profile, it is possible to think of the generating gear as the rack that defines the skiving tool profile. Therefore, the variation in centre distance, producing the tool conicity, is analogous to applying a varying profile shift coefficient x_T throughout the tool usable height, with the generating gear acting as the rack to the skiving tool profile being generated. As a result, Eq. (3) can be rewritten as:

$$x_T = \frac{\sum_{i=1}^n h_i \cdot \tan(\alpha_c)}{m_n} \quad (4)$$

During the tool profile calculation, the generating gear is brought closer to the tool profile with the increase of the re-sharpening depth. Hence, the tool profile shift coefficient of Eq. (4) decreases at each re-sharpening depth from the tool SOL to its EOL.

Moreover, from Eq. (4), for the same re-sharpening depth and clearance angle, tools with a lower normal module experience a higher variation of profile shift. In addition, it is known from the theory of gearing that gears with a small number of teeth change the shape more significantly for the same value of profile shift coefficient, as shown in Fig. 2. It can therefore be concluded that conical tools with a few teeth and smaller normal module are those whose profile changes the most between the tool SOL and the tool EOL.

For commercial reasons, tool manufacturers seek to ensure a usable tool height of about 5-20 mm. Then, during the tool design phase, a value for the clearance angle α_c in the range of 2° - 10° that allows collision avoidance is chosen. As a result, it

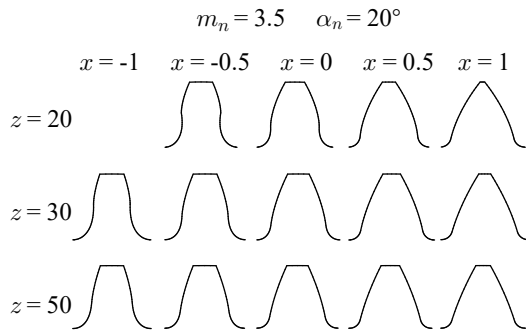


Fig. 2. Effect of the profile shift coefficient on gears with different number of teeth.

is not rare in practice to find tools with the highlighted geometric features, i.e. few teeth and a small module, that undergo a considerable variation in the cutting profile shape during their service life.

In an experiment recently proposed in [12], it was shown that reducing the profile shift coefficient may be beneficial for skiving tools. According to this, conical tools should perform better at the EOL compared to the SOL.

3. Analysis of cutting profile change: simulation

A routine, specifically developed by the authors in Matlab and based on [10], has been used to numerically compute the tool cutting profile at the SOL and EOL of two types of tool. Two case studies are then investigated. In each case study one type of tool, i.e. tool 1 and tool 2, at two re-sharpening stage, the SOL and the EOL, respectively, is used. The tools data for each case study are reported in Table 1.

In Fig. 3(a) the simulated profiles at the SOL and at the EOL of tool 1, are represented with a blue and red line respectively. Towards the tooth root, the active part of the cutting edge (continuous line), i.e. the part that effectively participates in cutting the workpiece, is distinguished from the root radii (dashed line) which are only a fitting and do not match with those of the real tool.

The cutting profile of tool 1 undergoes a significant change on its shape during its service life. This is because tool 1 has a large clearance angle which, despite the normal module not being particularly small, results in a variation of the profile shift coefficient of 0.5 over the service life. Referring to Fig. 2, such variation is significant for a pinion with 31 teeth and so it is also for tool 1. Pictures of tool 1 at the SOL and the EOL are

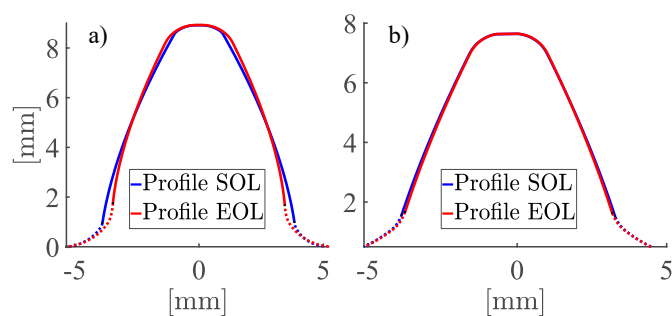


Fig. 3. Cutting profile at the SOL and at the EOL: (a) tool 1; (b) tool 2.

shown in Fig. 4(a) and (b), respectively. The effect of the bigger profile shift coefficient at the SOL that yields a bigger tooth base, and a more tapered tip can clearly be noticed. Furthermore, referring to Fig. 3 (a), when the tool is at the EOL it has a smaller active area of the cutting profile. Both these features make a considerable difference in tool performances as shown in the following Section.

Figure 3(b) shows the simulated profiles of tool 2. In this case the change in cutting profile between the SOL and the EOL is not significant. Compared to tool 1, the tool 2 has a smaller clearance angle, which produces a smaller variation in the profile shift coefficient of 0.3. However, the main difference compared to tool 1 is that tool 2 has 52 teeth, which makes it less sensitive to the effect of the profile shift coefficient, as shown in Fig. 2.

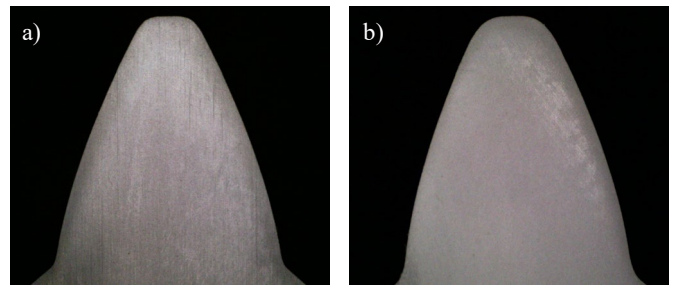


Fig. 4. Cutting profile of tool 1: (a) SOL; (b) EOL.

Table 1: Geometrical data of tool 1, tool 2, and of the gear they machine.

Data	Tool 1	Gear 1	Tool 2	Gear 2
Normal module [mm]	3.5	3.5	3.5	3.5
Normal pressure angle [deg]	20°	20°	20°	20°
Number of teeth	31	-67	52	-78
Helix angle [deg]	20° RH	Spur	20° RH	Spur
Profile shift coefficient (SOL - EOL)	0.5 - 0	0.03	0.85 - 0.55	-0.62
Usable height [mm]	10	-	10	-
Tip diameter [mm]	126	227.2	204.5	272.5
Root diameter [mm]	109.6	243.2	189.2	285.7
Rake angle [deg]	5°	-	5°	-
Clearance angle [deg]	8.5°	-	5°	-

4. Analysis of cutting performances: case study

For a skiving operation, the same process parameters, i.e. the number of passes, axial feeds and cutting speeds, are used regardless of the re-sharpening stage of the tool. As a result, when a skiving tool, undergoes a considerable variation in the cutting profile between the SOL and the EOL, it yields sub-optimal tool performances.

In what follows, a case study 1 and a case study 2 relative to tool 1 and tool 2, respectively, are investigated. For each case study, two process simulations, one with the tool at the SOL and one at the EOL are carried out. In addition, the corresponding process experiments are conducted to assess the validity of the simulation results.

The skiving process is simulated through the mathematical model developed in Matlab by the Authors. Besides the routine for the tool profile calculation at the different re-sharpening

depths, the model is based on the Boolean subtraction of surfaces and allows the calculation of working parameters such as working angles and chip thickness at all passes.

For what concerns the experiments, in each case study the same number of workpieces is machined with the tool at the SOL and that at the EOL. The experiments are carried out by a GLEASON PS600 machine tool and the process parameters related to each case study are reported in Table 2.

The Table shows that the number of parts machined as well as the process parameters, are different for the two case studies. This is due not only to the fact that tool 1 and tool 2 are different in design (Table 1), but also because the machined parts have different geometries and are made of different materials. Therefore, it is important to bear in mind that the following analysis is not intended to compare the performances of tool 1 with those of tool 2, but to compare in each case study the performances of the tool at the SOL and at the EOL.

Table 2: Process parameters relative to the two case studies.

Data	Case study 1	Case study 2
N° of passes	23	13
Chip thickness	0.15	0.15
Cross axis angle	20°	20°
Cutting velocity	60 m/min	80 m/min
Workpiece material	31CrMoV9	40CrMo4
Cooling	Oil	Oil
Tool material	S390	S390
Tool coating	AlCrN	AlCrN
N° of machined parts	30	50

4.1. Case study 1

The data reported in Table 1 and 2 are entered in the Matlab model. Then, the calculation is performed through the model, which first computes the tool geometry and then simulates the skiving process, resulting in the determination of the working parameters. Figure 5 shows the values of the working parameters for the pass n° 15. Particularly, Figs. 5a), c) and e), are relative to the tool at the SOL, whereas Figs. 5b), d) and f), are relative to the tool at the EOL. The abscissa reports the points in which the tool profile has been discretized as well as the corresponding cutting profile portions, i.e. the tip (T), the right flank (RF) and left flank (LF). The ordinates report the angular positions, assumed by the tool during the cut, that go from -20 to 20 degrees of rotation for the pass n° 15. On the right side of Fig. 5 the vertical colour-bars represent the values of the working parameters of those tool points that cut the gear gap during the pass.

From the figure, several differences between the cutting conditions of the tool at the SOL and at the EOL can be observed. Figures 5a) and b) show the chip thickness values for the tool at the SOL and at the EOL respectively. The tool at the SOL cuts with its tip a larger maximum chip thickness than the tool at the EOL. Also, comparing the rake angle values portrayed in Figs. 5c) and d) the smallest minimum rake angle is reached by the tool tip relative to the SOL. For what concern the clearance angle, portrayed in Figs. 5e) and f), both tools allow collision avoidance, but the tool at the EOL has less clearance during the cut.

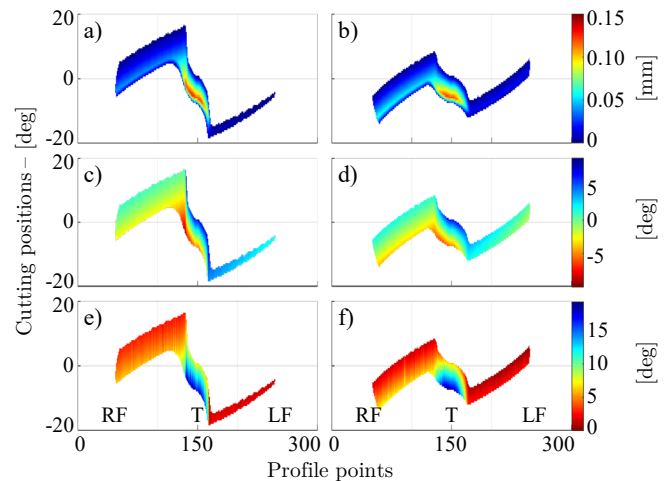


Fig. 5. Working parameters of pass n° 15: (a-b) Chip thickness; (c-d) rake angle; (e-f) clearance angle.

Notably, due to both the bigger tip diameter and the cutting trajectory it yields, the tool at the SOL begins earlier and ends later to cut the gear gap, resulting in a longer length of cut at each pass. In addition, when the cutting profile is close to the highest load conditions, i.e. when the chip thickness reaches its maximum and the rake angle its minimum, the tool at the SOL only works with a limited portion of the cutting tip profile. Moreover, such a high load condition is maintained for several cutting positions. The tool at the EOL, in contrast, works with a larger portion of the tip profile. Additionally, due to both the smaller tip diameter and the cutting trajectory it produces, it maintains the high load conditions for fewer positions compared to the SOL.

The conditions outlined above are observed in each of the 23 passes of case study 1. Hence, for an overall view of the process, the comparison between the cumulative machined total cutting length l_{cTOT} relative to all the passes cut by the profile at the SOL and at the EOL is shown in Fig. 6 a), in blue and red, respectively. In the figure, the cutting profile, depicted with the rake face entering the paper, is also illustrated. The solid line represents the SOL, while the dashed line represents the EOL. The portion of the cutting profile that cuts the most is the right radius of the tip. At the SOL this profile portion machines for each workpiece 60% more l_{cTOT} compared to the tool at the EOL, which is a remarkable difference. The longer permanence at high load cutting conditions and the bigger

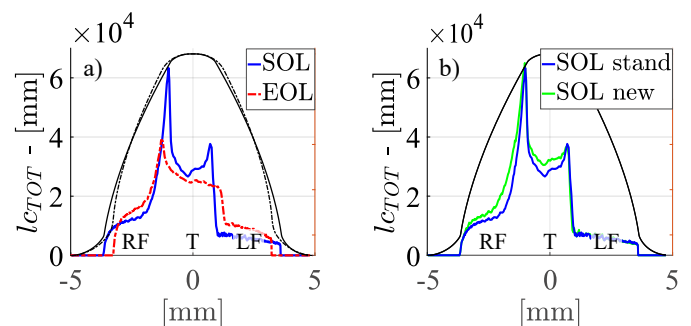


Fig. 6. Comparison of the cumulative total machined cutting length between a) SOL and EOL with the standard process parameters; b) SOL with standard and with the new process parameters.

values of l_{cTOT} are expected to yield a significant difference in how the tool at the SOL wears compared to that at the EOL.

It is worth noticing that the simulation results are consistent with the experiment shown in [12]. Tools with a smaller profile shift coefficient, in this case the tool 1 at the EOL, exhibit a reduced length of cut, smaller maximum chip thickness and operate with more positive values of rake angle.

In order to assess the validity of the simulation results, experiments for case study 1 are carried out. Figure 7 reports the wear conditions of the rake face and the tip for tool 1 at both the SOL (Fig. 7a) and at the EOL (Fig. 7b), after machining 30 workpieces. The cutting profile portions, (RF, T, LF) are also reported in the figure. The tip is the most worn part of the profile, which is typical in the skiving process. According to the simulation results, it experiences the highest load and removes the most material during cutting.

Notably, there is a marked difference in the amount of wear on both the rake face and the tip between the tool at the SOL and at the EOL. Specifically, the tool at the SOL result to be twice as worn compared to the one at the EOL, despite having machined both 30 workpieces with the same process parameters. The experiment has been repeated several times producing the same results.

The experiment outcomes suggest the correctness of the simulation results and are in line with what was observed in Section 2, i.e. tool 1 is subject to a significant change in the shape of its profile during its service life which leads to significant differences on cutting performances.

4.2. Case study 2

Since the cutting profile change is not significant for tool 2, there is almost no difference between the simulation results of the tool at the SOL and at the EOL. Therefore, for the sake of conciseness, only the results of the experiments are reported in the following.

Figure 8 shows the wear conditions of the rake face and of the tip for tool 2, after machining 50 workpieces, for both the tool at the SOL (Fig. 8a) and at the EOL (Fig. 8b). Overall, the wear is distributed rather evenly over the tip and, there are no substantial differences in the way the tool has worn at the SOL compared to the EOL. This is also in accordance with what observed in Section 2, i.e. the cutting profile of tool 2 does not change significantly during its service life and consequently

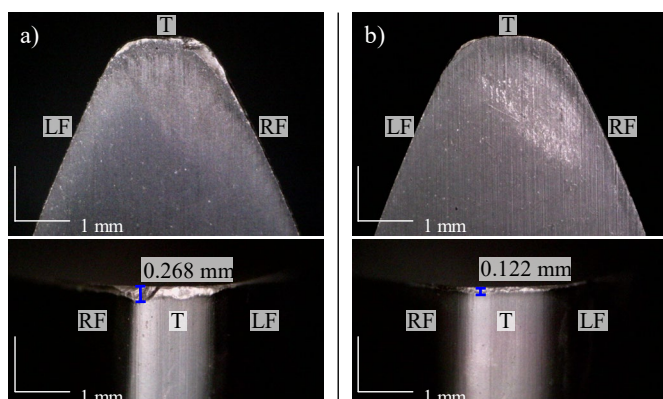


Fig. 7. Wear on tool 1 after machining 30 workpieces: a) SOL; b) EOL.

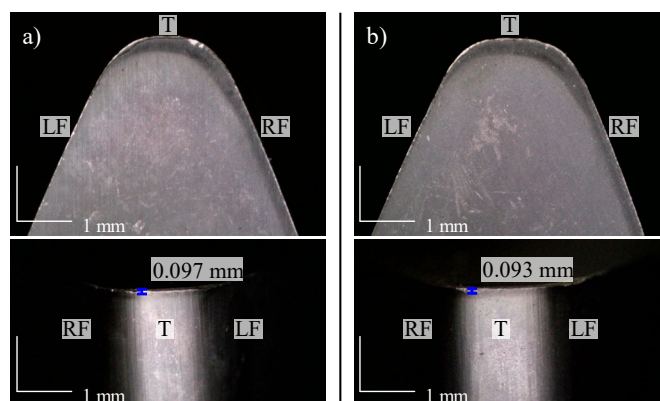


Fig. 8. Wear on tool 2 after machining 50 workpieces: a) SOL; b) EOL.

neither do the cutting performances.

5. Performance homogenization

A significant difference in cutting performance between tools of the same type at the SOL and at the EOL can cause issues in the production of large batches since tools should be replaced at different times to avoid failures.

To enhance the tool performances at the SOL, adjustments must be made to align the cutting conditions with those of the tool at the EOL. Ideally, the load on the tool tip and the cumulative total machined cutting length should be both reduced. With these objectives, using the simulation model, a new set of process parameters has been computed for case study 1 which is reported in Table 3. Specifically, to ease the high load condition, the nominal maximum chip thickness has been decreased from 0.15 mm to 0.12 mm. However, reducing the nominal chip thickness also decreases the axial feed rate, leading to an increase in the number of cuts and consequently in l_{cTOT} . Therefore, the number of passes is reduced from 22 to 14. Figure 6b) compares the values of l_{cTOT} achieved by the tool at the SOL using the new process parameters, depicted in green, with those achieved by the tool at the SOL with the standard process parameters, shown in blue. Remarkably, despite the decreased load on the tool, the values of l_{cTOT} are maintained.

Then, 30 workpieces have been machined by the tool at the SOL with the new process parameters of Table 3. The resulting tool wear on the rake face and at the tip are shown in Fig. 9. By comparing Fig. 7 with Fig. 9 it appears that the wear values of the tool at the SOL operated with the new process parameters match the wear of the tool at the EOL operated with the standard process parameters. This once again demonstrates the

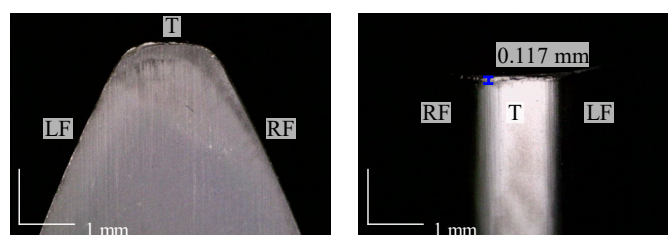


Fig. 9. Tool wear on tool 1 at the SOL after machining 30 workpieces with the new process parameters.

effectiveness of the simulation results that can be efficiently used for the optimisation of the skiving process. It can be concluded that by adopting two different sets of process parameters, one for the tool at the SOL and one for the tool at the EOL, the cutting performances may be effectively homogenized.

Table 3: New process parameters for case study 1.

N° of passes	Chip thickness	Cross-axis angle	Cutting velocity
14	0.12	20°	60 m/min

6. Discussions

This study shown that during the service life, conical tools may undergo a significant change in the cutting profile which affect the cutting performance. For the same usable height and the same clearance angle, conical tools with a small module and few teeth are the most sensitive to the change in cutting profile.

A model for the simulation of the skiving process was developed by the Authors and two case studies were analysed. In case study 1, a considerable change in the tool cutting profile was observed, whereas in case study 2 the change was negligible. The simulation revealed that for case study 1 with the same process parameters, the tool at the SOL is operated in more severe cutting conditions with respect to the tool at the EOL.

To prove the validity of the model, skiving experiments have been conducted for both case studies. In case study 1, for the same number of parts machined, the tool at the SOL wore twice as much than at the EOL. In case study 2 the difference in tool wear between SOL and EOL was negligible. The results of the experiments strongly agree with those of the simulation model, suggesting its validity.

Considering the marked difference in performance of the tool in case study 1, with the aid of the simulation model, a new set of process parameters for the tool at the SOL was proposed for case study 1. The rationale was to ease the cutting conditions for the tool at the SOL. The new process parameters have been tested by skiving experiment showing the effectiveness of the new process strategy and of the simulation model.

The idea of using two different process strategies, one for tools toward the SOL and one for tools closer to the EOL, is strongly recommended when the tool is sensitive to major change of the cutting profile. If only one set of process parameters that works well for the tool at the EOL is used, it may lead to poor performances of the tool at the SOL (Fig. 7). On the other hand, the set of process parameters designed for the tool at the SOL may not be suitable for a tool at the EOL. Indeed, the tool at the EOL features both a reduced thickness at the tooth root and a low usable height, both features that compromise the bending strength of the tool teeth. Since the process parameters proposed for the tool at the SOL may yield a high bending load to the tool due to bigger radial passes, they may trigger vibrations that may result in low workpiece quality, and eventually to tool breakage in extreme cases.

7. Conclusions

In this paper, the effects of re-sharpening on conical skiving tools were investigated. The geometric parameters that characterize the most sensitive conical tools to cutting profile change due to re-sharpening were identified. To analyze the effect of the cutting profile change on cutting performance, a simulation model for the skiving process was proposed. Two case studies were simulated, and the results of the experiments proved the validity of the simulation model. In addition, a process strategy for homogenizing the cutting performances between the tool at the SOL and at the EOL was proposed using the simulation model, then its effectiveness was proven by experimental results. In a future study, a coefficient that limits the maximum variation of the profile shape depending on tool geometry will be proposed and used for optimal design of conical skiving tools.

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