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Power skiving manufacturing process: a review

Enea Olivoni^a, Rocco Vertechy^a, Vincenzo Parenti-Castelli^a

^aDepartment of Industrial Engineering, University of Bologna, Viale del Risorgimento 2, Bologna, Italy.

Abstract

Gears are the most widely used mechanical components for motion and power transmission; thus, gear manufacturing plays a crucial role in many industrial sectors. Among the different methods for gear machining, power skiving has become a highly competitive gear manufacturing process in the last few decades. This is mainly due to advances in manufacturing engineering and improvements in numerical control of electric drives. This article presents a comprehensive review on the research and development activities on power skiving that is missing in the literature. In particular, it aims at presenting the current state of the art of this manufacturing process and highlighting new advancements. The study encompasses some of the major topics, namely: new tool designs, influence of working parameters on the cutting operation, chip geometry, determination of cutting forces and tool wear. Finally, study deficiencies, practical limitations and new research directions in the field of power skiving are discussed which can serve as guidelines for new research on the topic.

1 Introduction

Power skiving, in the literature also referred to as scudding or slicing, is a machining process for gear production. It was originally developed and patented in 1910 [1]. However, innovative as the patent was at that time, the machining technology of those days was insufficient to meet the highly demanding requirements inherent in the process. Among them, the most problematic ones were: the high stiffness of the machining apparatus, the perfect motion synchronisation needed between the tool and the workpiece, and the necessity for durable tool materials. After a dormant period of more than 50 years, the skiving process only found some rare applications in the 1960s and 1970s when it was used for internal gears manufacturing.

With the advancement in manufacturing technology and novel tool coatings, nowadays power skiving has become a highly competitive technology in gear production. Compared to the most common gear machining processes such as gear hobbing, broaching and shaping, power skiving offers significant advantages. Unlike gear hobbing, it also allows internal gears to be cut and it is more flexible than broaching. Although shaping is the most applied cutting method for internal gears, the lack of material removal during the back stroke negatively affects the process productivity [2]. In contrast, power skiving is a continuous cutting procedure. Its uninterrupted material removal increases the production compared to both shaping and hobbing [3,4].

As in many other machining technologies, the successful application of power skiving depends on several issues that are of great research interest. However, despite the recent spread of power skiving among gear companies, only a part of these issues has been investigated so far, and there were few published papers before 2010. Since then, research centres and universities have been putting great attention to this technology and to the factors that influence it.

In order to foster the research in power skiving, it is worth emphasizing the key issues of the process along with the accomplishments made by researchers so far. To the authors knowledge, a systematic review that portrays the state of the art on power skiving is still missing. Therefore, in the present work, the relevant researches in the field of power skiving and their developments are presented with the aim of summarizing the major findings, establishing the current state of the art and highlighting new research directions of the process. To this end, an investigation was performed focusing the attention on the scientific literature rather than on technical papers. The reason of this choice is to encourage the definition of new mathematical models that can bring new insights on power skiving. With the best of the authors' effort, the full set of scientific articles to date published in English on this matter has been reported, although it is possible that some papers have been overlooked. As a result, more than seventy papers on power skiving were considered and classified based on the rationale reported in what follows.

Several aspects are involved in the process. Among them, the gear quality and the cutting conditions that determine the rate at which the tool wears during the operation are the most relevant ones, thus they are considered as the key issues of the process in this paper. The reasons for this conclusion are that while the gear quality represents the qualitative outcome of the process, the cutting conditions determine its cost in terms of tool wear and cutting time. Therefore, a skiving application should be evaluated considering these two key issues by weighing the quality obtained with the price paid to get it.

Many studies on power skiving are available in the literature aiming at either improving the two key issues and hence the process, or at helping for a deeper understanding of it. From the literature survey, three major themes emerged which have been adopted in this review to sort papers within corresponding groups. Papers not clearly dealing with the three major themes are reported in a fourth group. In particular, the first group, defined as *cutting process principle and simulation*, includes articles which developed simulation procedures to analyse key factors that are difficult to measure. The second group, defined as *parameter influence on the process*, encompasses articles in which the influence of certain parameters and their variation on the gear quality and the cutting conditions are studied. The third group, defined as *tool design*, comprises articles dealing with the key role of the tool geometry on the full process. The few articles that do not cover any of the above-mentioned major themes were gathered in the fourth group defined as *miscellaneous* group.

Therefore, four groups representing the current state of the art of the power skiving process are reported in this review. It is worth noticing that a perfect attribution of the analysed papers to only one of the four groups is not always possible since some papers may belong to more than just one group. In these cases, the paper is cited in all pertaining groups. Despite some overlapping, the grouping method presented in this work is highly suitable to provide a clear overview on the current state of the art of power skiving.

The rest of this paper is organized as follows. In the next section, the tool geometry and the kinematics of power skiving are briefly presented along with the key words related to the process. Then, dedicated sections for each group in which the articles have been divided are presented. Within each section, the contents of the considered papers are summarized and listed in tables. Finally, a discussion on study deficiencies, practical limitations and possible future developments is reported, followed by a conclusions section.

1.1 Geometry and kinematics of power skiving

Power skiving is a high-speed method for manufacturing gears where a pinion shaped cutter is used to machine the teeth of the desired gear. The skiving tool resembles a gear shaping cutter, since it is essentially an external gear with modifications to optimize machining. Skiving cutters may be spur or helical as shown in Fig. 1. In the first case the cutter teeth width develops parallel to the direction of the tool rotation axis. In contrast, observing an helical tool, the teeth are inclined with respect to the tool rotation axis. This inclination is referred to as the *helix angle*, which is defined as the acute angle between the tangent to the tooth helix and the straight generator of the cylinder on which the helix lies. This definition applies for helical gears as well. In what follows the helix angles of the tool and the gear are measured on the pitch cylinders and are labelled as β_t and β_g , respectively (Fig. 2a).

Geometrical differences between spur and helical tools have an impact on the type of workpiece that can be machined. When workpiece and tool are in mesh, their helix angles determine the *shaft angle* Σ . This is defined as the smallest angle through which one of the axes must be swivelled so that the tool and gear axes become parallel (Fig. 2). In particular, in order for the cutter and workpiece to mesh, the following equation must hold:

$$\Sigma = \left| \beta_t + \varepsilon \beta_g \right| \quad (1)$$

where the parameter ε has a value equal to 1 if the meshing gears are external or -1 if they are internal. The formula assumes that both gears have the same helix direction. Differently, ε assumes opposite values, namely -1 for external and 1 for internal gears. When the cutter or the gear is spur, the respective helix angle is zero.

Besides, referring to Fig. 3a and using basic trigonometric relations, it is possible to establish the equation that associates the magnitude of the *tool peripheral velocity* v_t with that of the *cutting velocity* v_c at the point P of tangency of the pitch cylinders, which lies along the shortest distance between rotation axes:

$$v_c = \frac{v_t \sin \Sigma}{\cos \beta_g} \quad (2)$$

It is evident that when Σ goes to zero, the cutting velocity also vanishes resulting in null cutting action. Observing Eqs. (1) and (2), it can be concluded that spur cutters can machine helical gears only, whereas helical cutters can cut both spur and helical gears.

The distinction between spur and helical cutter also affects the geometry of the tool rake face. In particular, spur cutters have conical rake faces (Fig. 1a), whereas helical cutters usually adopt planar rake faces (Fig. 1b). The tool *rake angle* α_r is machined on the front face of each tooth.

For spur cutters, α_r is defined as the angle between the transverse plane, orthogonal to the tool rotation axis, and the conical rake face generatrix, which is unique for the tool teeth (Fig. 3a). The rake angle strongly influences the cutting conditions. In case of helical tool, its definition is more complicated since each tooth has its own rake face whose orientation includes the effects of



Figure 1: a) Spur cutter; b) helical cutter.

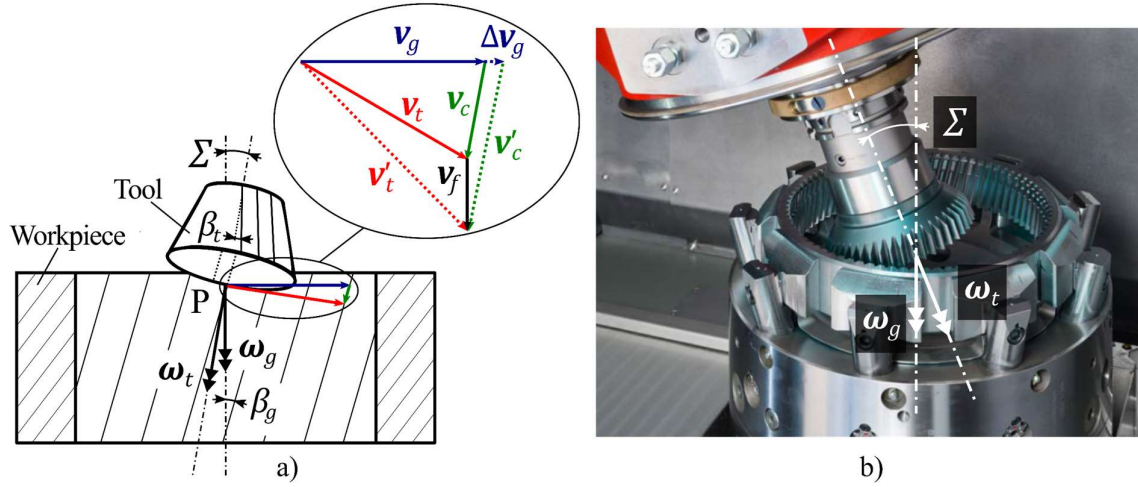


Figure 2: a) Velocity triangle of point P; b) power skiving process.

both the helix angle and the tool rake angle. This arrangement of the rake face allows an even distribution of the load, and consequently of the wear, on the cutting edges compared to spur tools [5].

In order to define the rake angle and illustrate its role in defining the rake face orientation in a helical cutter, the steps taken to determine the rake face of a single tooth are presented in what follows. To this end, Fig. 3c shows a reference frame $O(x,y,z)$ fixed to a single tooth, with unit vectors i, j, k and the tool design planes, i.e. the transverse plane and the rake face, based on which the tooth cutting profile is defined. The x and y axes lie on the tool transverse plane whereas the z axis points upwards. Furthermore, the reference frame origin O is placed coincident with the tooth tip and the x axis is set collinear with the tooth axis of symmetry. By rotating a unit vector originally coincident with the unit vector j about the x -axis of the helix angle β_t , the vector j' is found. Similarly, by rotating a unit vector originally coincident with the unit vector i about the y -axis of the rake angle α_r , the vector i'' is determined (Fig. 3c). It is worth noting that unit vectors j' and i'' are not perpendicular to each other. Using the cross-product on the calculated vectors, it is possible to determine the unit vector normal to the rake face n_r . The unit normal vector, along with the reference frame origin $O(x,y,z)$, completely defines the tool rake face. The rake face normal vector n_r is represented in Fig. 3c along with the normal vector n_t to the transverse plane.

From what reported above, it can be concluded that differently from the case of spur cutters, in helical cutters the rake angle alone does not define the orientation of the rake face. The orientation is determined only when both helix angle and rake angle are specified.

Another distinction among cutters can be made based on their external shape. This is usually either cylindrical or conical. In conical tools, a *clearance angle* α_r is machined on the tip surface. This entity, also referred to as *top relief angle*, can be defined as the angle between the cutter external cone generatrix and the rotation axis of the cutter (Fig. 3b). The function of α_r is to assure that the cutter doesn't scratch the machined surface. Therefore, in case of cylindrical tools, a *tilt angle* δ must be provided by tilting the cutter during machining to allow enough instantaneous clearance angle on the external diameter, between the workpiece

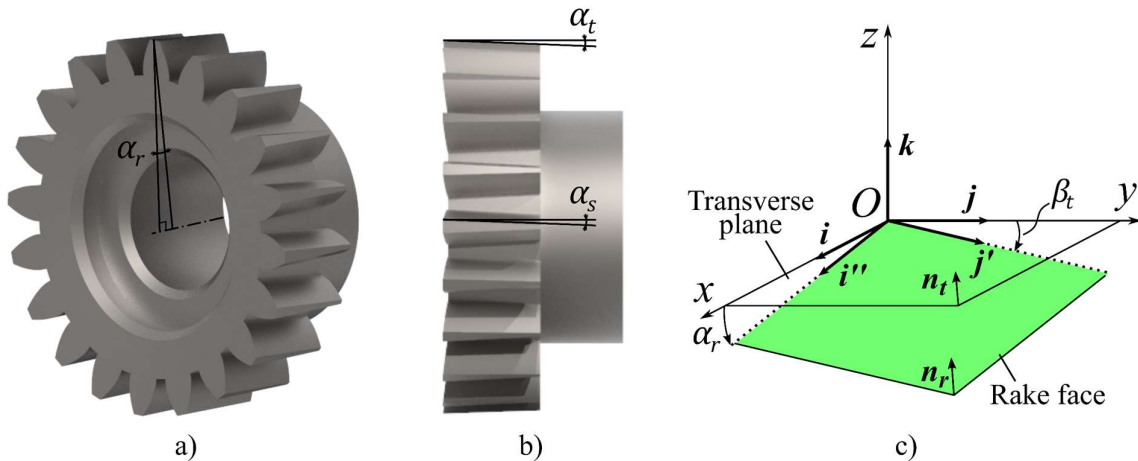


Figure 3: a) Tool rake angle; b) tool top and side relief angle; c) tool design planes.

and the tool. On the other hand, no tilt motion is necessary with conical tool, but re-sharpening could lead to addendum modifications on the tool teeth, resulting in major profile differences on the workpiece [6].

Besides, by intersecting the flank of a cutter tooth with its pitch cylinder it can be observed that the two obtained lines tend to converge and are not parallel to each other. In particular, the tooth flanks of a spur skiving tool result pointed along the tooth width (Fig. 3b), whereas those of a helical cutter are pointed along its helix. This inclination is defined as the *side relief angle* α_s , which is machined on the skiving tools to avoid the flanks of the cutting teeth rubbing against those of the workpiece.

Eventually, as far as the tooth profile is concerned, this is usually an involute with additional corrections to enable proper machining and to avoid interferences. However, other profile geometries might be chosen as presented in [7].

It must be noted that the angles described so far are those machined on the tool surface and are constant once the tool geometry is chosen. However, as a result of the tool-workpiece interaction, another set of angles can be defined that vary for each point of the tool profile and for each instant. These are usually referred to as working or *instantaneous angles*. The interested reader can refer to [8] for their definition.

From the kinematic point of view, tool and workpiece rotate synchronously at a high speed as a pair of mating gears with skew axes as shown in Fig. 2b. Initially, the workpiece blank is a cylinder or a ring, depending on whether the gear to be cut is external or internal, respectively. Then, cutting is performed in several passes wherein the tool is set at a radial cutting depth and fed axially along the face width of the gear at a set feed rate. At each pass the teeth of the workpiece gear take shape. The continuous cutting action is produced by the relative velocity, namely the cutting velocity, developed at the engagement points between tool and workpiece. The cutting velocity at point P is directly influenced by the peripheral speeds of skiving tool and workpiece, \mathbf{v}_t and \mathbf{v}_g , and by the shaft angle as shown in Eq. (2). The shaft angle is usually set to 20° as a trade-off between optimal cutting parameters and interference avoidance [9].

When necessary, other motions could be added to the process. Whenever the gear to be cut is helical instead of spur, and the tool is fed axially with velocity \mathbf{v}_f , the angular velocity of the workpiece gear must be varied in modulus by a quantity $\Delta\omega_g$. In particular, in order to remain in mesh, workpiece and tool must have the same velocity component on the normal direction to the helices at the point of contact. With reference to Fig. 2a, it can be seen that when the feed motion is added to the tool, the peripheral velocity of the cutter at point P changes from \mathbf{v}_t to \mathbf{v}'_t . For the tool and gear to remain in mesh, the cutting velocity \mathbf{v}_c must retain the same direction tangent to the helix. Therefore, the gear peripheral velocity modulus at the cutting point must be varied by the quantity Δv_g . Considering the relation between the modulus of the gear peripheral velocity and angular velocity, and the gear pitch radius r_g , the following equation must hold:

$$\Delta\omega_g = \frac{v_f \tan \beta_g}{r_g} \quad (3)$$

As mentioned above, for cylindrical cutters which have insufficient clearance angle, a tilt motion should be added to avoid interference with the workpiece. Extra movements can be applied to the tool in order to make gear tooth modifications [10].

2 Group article review

2.1 Cutting process principle and simulation

This section includes the papers dealing with the simulation of the power skiving process. The survey of these papers shows that the most commonly analysed elements in power skiving simulations are the chip geometry, the cutting forces, the operating temperatures, the cutting parameters and the tool wear. Prediction of the influence of these elements allows the process optimisation in terms of tool durability and workpiece quality, enhancing production and efficiency.

Unfortunately, the interaction between cutter and workpiece during the skiving process is very complex. Cutting parameters including cutting velocity, instantaneous rake angle and depth of cut, vary continuously both along the cutter and at different engagement phases with the workpiece. Due to this complexity, several power skiving simulations are carried out using sophisticated tools like CAD, CAM or FEM commercial software. However, commonly user-oriented software can only perform simulations that are limited by the simplifications and assumptions made to facilitate their use. In a novel and evolving technology as power skiving, it is advisable to take into account as many parameters as possible. For this reason, ad-hoc software and numerical simulations are considered the best options to simulate the process.

Spath et al. [6] were among the first to develop a dedicated software for skiving. This allowed for the design of the tool shape and the computation of the cutting parameter values. In [11] Schulze et al. developed a 3D model of the process using the FEM commercial software ABAQUS. The authors validated the model experimentally, through a comparison of the simulated deformed chip shape, process forces and temperatures, which were the results of the simulation. In [12] Klocke et al. calculated the chip thickness, the cutting velocity and the actual rake angle using SPARTApro, a software originally developed for hobbing simulations and then adapted to power skiving. Considering the software promising accuracy, it has been used to validate the uncut chip analytical model presented in [13] and the skiving model presented in [14]. The latter allows a fast computation of the extreme values of the process parameters as the uncut chip thickness. Furthermore, to prove SPARTApro's reliability, skiving simulations were successfully validated through real skiving machining in [15].

A key factor in power skiving is the uncut chip geometry (UCG), since its determination can be exploited to compute several aspects inherent of the process, such as cutting forces and operating temperatures. The UCG may be determined analytically, generally using simplified representations of the real tool geometry in order to reduce equation complexity. However, due to the

development in computer technology, it is now possible to employ modern solid geometry modellers to produce accurate representations of the UCG. This is achieved by using the swept volume generated by the movement of the cutter profile. The interference between the swept volume and the workpiece volume gives the UCG. This procedure is referred to as solid modelling [16]. A graphical example of it is given in Fig. 4, which represents the groove of a workpiece being machined, the volume swept by the cutter profile and the resulting UCG. However, there are different ways to represent the workpiece geometry. A distinction can be made between exact solid modellers and discrete volume solid modellers. The former, though accurate, are computationally expensive, whereas the latter are usually faster, at the expense of accuracy. From the literature survey, it emerges that several scholars employed solid modelling to compute the uncut chip geometry. To accomplish this, they used volume interference methods, usually employing discrete modellers to represent the tool and the workpiece.

In [17] researchers used the discrete Z-map method for solid modelling, where vertically oriented line segments describe the workpiece geometry. In [18], Ren et al. calculated the uncut chip through the Z-map method as well, and devised an oblique cutting model to compute the cutting parameters. These were used as entries of a FEM software which allowed the calculation of both temperature and local stress of the cutting zone and eventually of the tool wear-crater prediction. Experimental results demonstrated that the correlation between simulated and real crater was within 5% error.

Other authors [19,20] employed the triple Dixel format which is an extension of the Z-map method in three orthogonal directions. The use of the triple Dixel representation, which is computationally more expensive, is justified by a more accurate description of the represented volume. Indeed, when the volume sections run parallel to the line segments of a Z-map model, poor surface representation may arise. To compute the 3D uncut chip, in [19] McCloskey et al. employed the ModuleWorks software engine, which is an optimized multi-Dixel solid modeller. By intersecting the 3D chip with the tool rake face, they obtained the final 2D chip geometry, which was used as entry for a Kienzle model to estimate cutting forces. In order to validate the model, they also performed experimental cutting trials with strain gauges on the tool holder allowing both the computation of the Kienzle model constants and the comparison between measured and estimated forces. Recently, Inui et al. [20] defined the thin swept volume of the cutting edge as a polyhedral model and converted it in triple-Dixel format. After subtracting it from the workpiece, they obtained a triple Dixel representation of the chip.

A different technique that allows UCG computation has been employed by Fang et al. in [21]. The authors used level contour method to thoroughly analyse the 3D chip under different cutting conditions. This method was also used to compute the UCG in [22], from which the local cutting parameters were derived.

An alternative to carrying out solid modelling is through CAD software. In [23,24], Antoniadis et al., presented a skiving process simulation in a CAD environment. In particular, they presented a novel software for skiving. This was the extension of previously devised software packages for other machining processes. After calculation of the 3D UCG, using the novel code they computed 2D chip sections through the knowledge of the tool rake face position. These were employed in a Kienzle model to predict cutting forces. Tapoglou computed the non-deformed 3D UCG and the cutting forces in a similar fashion in [25,26]. Besides, he found a good correlation comparing simulated force data with literature results. Despite the interesting results, the use of CAD based software tends to be more arduous than the previously presented simulation methods; thus, good programming skills are required for its efficient use.

As shown, one way to carry out cutting force calculation is to employ 2D chip sections as entries in a cutting model. To obtain chip sections, many authors took slices of the previously calculated 3D UCG. However, this is not the only available possibility to compute cutting forces. In fact, some researchers directly discretized the cutter in points or micro sections. Once the geometry and kinematics of the process are known, it is possible to numerically compute the width and depth of cut relative to each discretized domain. For each of these, it is possible to apply an oblique cutting model to compute local forces, which could be finally summed up to obtain the resulting process forces. This technique has the advantage to be computationally faster with respect to the solid modellers methods since volume representation is not required during the simulation. However, few information on the 3D UCG can be drawn.

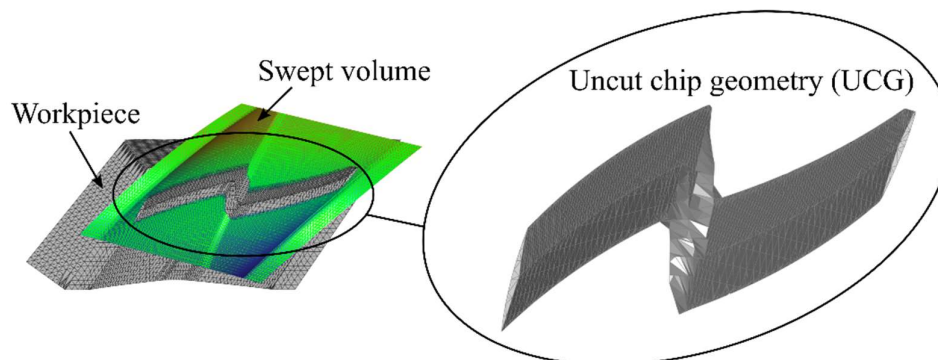


Figure 4: Uncut chip geometry obtained through solid modelling.

In [27] the tool was divided in microsection edges and the computed force values were compared with a FEM simulation showing a good match. Likewise, in [28] the tool profile was divided into a set of cutting-edge elements, each of which was used in an oblique cutting model to compute the cutting conditions and the local forces. In [29] Vergas et al. implemented an iterative model for skiving process based on the one presented in [6]. They modelled the tool as a point cloud in movement relative to the workpiece. Using a Kienzle model, they correlated the effect of the rake angle decrease with the cutting force increase, by employing different tools. Cutting trials were carried out to validate the results. Similarly, in [30], cutting forces were modelled considering the change in effective rake angle during the process. In addition, an identification method of cutting force coefficients with a skiving tool that has multiple cutting edges was proposed, then the results were validated by cutting tests. Oblique cutting model applied to microsections was also employed in [31]. In this work, Wu et al. considered the influence of the computed cutting force and the velocity, along with the chip contact characteristics, to develop a temperature calculation model. The model was validated with the aid of a thermal imager and thermocouples. Then, [32] Wu et al. investigated the chip formation and force calculation in gear skiving when an arc-tooth cutter is employed. Their results were confirmed through real cutting trials. Recently, [33] Zhang et al. developed a numerical model to dynamically predict the thermomechanical coupling of cutting forces and cutting temperatures during the skiving process. The model is based on previous studies conducted by the author's team [27,31]. The mapping between cutting parameters, cutting forces and temperatures was established and validated through experiments.

To avoid a long-winded section, only the major key factors considered in the examined papers have been discussed. However, for the sake of completeness and clarity, all the key factors reported in each article of this section have been summarized in Table 1. In particular, some additional information can be drawn from the table. For instance, the chip thickness or the uncut chip geometry have been evaluated not surprisingly by almost all the authors. Indeed, the chip is representative of the cutting process and it is also necessary for further calculations such as that of the cutting forces. Moreover, the cutting forces and the cutting parameters were simulated in many papers, while the operating temperature and the tool wear have been treated in only a few studies. Indeed, the phenomena linked to the tool wear and the operating temperature, which are linked to each other, are difficult to understand since several factors are involved. Since the cost of the entire operation depends on the tool wear, then the development of further studies on this topic is advisable.

2.2 Parameter influence on the process

Achieving a better knowledge of the cause-effect relations that exist among process parameters means acquiring a deeper comprehension of the machining process. Before listing the various research works that were conducted in this area, the definitions of the different sets of addressed parameters must be given since they vary across the literature.

In this article, the sets are distinguished between *set-up parameters*, *tool parameters* and *cutting parameters*. In particular, the *set-up parameters* are those that the operator, who manages the interface with the skiving machine, can modify depending on the specific machining operation. These include the tool shaft angle Σ , the rotation axes shortest distance d , the tilt angle δ , the axial and radial feeds of the tool, respectively f_a and f_r , and the angular velocities of tool and gear, respectively ω_t and ω_g . Furthermore,

Table 1: Key factors simulated in the papers dealing with cutting process principle and simulation.

Authors	Ref.	Uncut chip geometry	Chip thickness	Cutting forces	Operating Temperature	Cutting Parameters	Tool wear
Spath et al.	[6]		✓	✓		✓	✓
Schulze et al.	[11]			✓	✓		
Klocke et al.	[12]		✓			✓	✓
Bergs et al.	[13]		✓				
Vargas et al.	[14]		✓	✓		✓	
Janßen et al.	[15]	✓	✓				✓
Nishikawa et al.	[17]	✓					
Ren et al.	[18]	✓	✓	✓	✓	✓	✓
McCloskey et al.	[19]	✓	✓	✓		✓	
Inui et al.	[20]	✓	✓				
Fang et al.	[21]	✓	✓				
Z. Ren et al.	[22]	✓	✓	✓		✓	
Antoniadis et al.	[23]	✓	✓	✓			
Antoniadis et al.	[24]	✓	✓	✓			
Tapoglou	[25]	✓	✓	✓			
Tapoglou	[26]	✓	✓	✓			
Li et al.	[27]		✓	✓		✓	
Guo et al.	[28]		✓	✓		✓	✓
Vargas et al.	[29]		✓			✓	
Onozuka et al.	[30]		✓	✓		✓	
Wu et al.	[31]		✓	✓	✓		
Wu et al.	[32]	✓	✓	✓			✓
Zhang et al.	[33]		✓	✓	✓	✓	

the set-up deviations, SU_{dev} , namely the variations of the aforementioned set-up parameters from their nominal values, are also considered in this group. The *tool parameters* are intended as those depending on the tool shape. These encompass all gear characteristic elements, such as: the tool number of teeth z_t , the normal module m_n , the tool helix angle β_t and the tool modification factor x_t . Tool cutting angles like the rake angle α_r , the clearance angle α_t and the side relief angle α_s are also included in this group. The re-sharpening depth h_r is comprised as well, and it is usually quantified in terms of axial shift from the rake face of the new tool. In addition, the tool shape deviations from the theoretical shape, such as for instance the tool run-out and the pitch deviations, are also included and named as TS_{dev} . Finally, the *cutting parameters* are those that depend on the interplay between kinematics and geometry of the process. These are the instantaneous rake and clearance angles, depth of cut, cutting velocity and all the other elements which result from the tool and workpiece instantaneous interaction. The measure of the interference between cutter and workpiece is comprised as well.

The literature survey highlights that only the set-up and tool parameters variation have been analysed. Depending on which implications due to parameter variations have been addressed, it is possible to make three distinctions among articles of this section. Indeed, a significant number of papers focus on the influence that the set-up and tool parameters have on cutting parameters. A second portion focuses on their effect on gear profile and tooth surface quality, whereas the last portion shows their influence on tool wear. As mentioned in the introduction, these implications reflect the will to improve the power skiving process and, hence, the obtainable gear quality and tool durability.

As far as the influence on cutting parameters is concerned, the effect of set up and tool parameters on the instantaneous top and side relief angles has been assessed in [34]. In [35], the influence of tool rake angle, relief angle and feed motion on the interference between tool and workpiece is studied by means of a graphical analysis. A similar study was conducted in [36], in which the effect of the tooth number, tool modification factor, rake angle and relief angle on the interference was analysed. In [37], Guo et al. studied the effect of the tool teeth number and the shaft angle on the instantaneous rake angle. They also investigated the influence of different tool teeth numbers and the axial feed on the lead deviation. Furthermore, in a recent study, the same authors compared the variation of the rake angle of an ordinary skiving tool to that of a multiblade cutter during the engagement with the workpiece [38].

In [12], Klocke et al. investigated how the tilt angle, shaft angle, tool teeth number and tool modification factor affected the chip thickness, the rake angle, and the cutting and sliding velocities. By doing so, the authors were able to select the tool teeth number that allowed a good trade-off between productivity and cutting conditions to machine a test gear. Then, they studied the chip thickness and the tool wear for the defined tool with four different process set-ups. An insight on chip clamping and welding for the four different set-ups was also given.

In [39], the influence of the tool teeth number, tilt angle and the profile shifting coefficient in cutting parameters were analysed. After establishing an oblique cutting model, in [40] Moriwaki et al. studied the effect of the shaft angle and the tool face offset on the instantaneous rake angle, the clearance angle and on the depth of cut. Soon after, Uriu et al. continued the study of the research group in power skiving [9]. They gave foundation for the common choice of setting the shaft angle to 20° . The analysis of the cutting parameter values demonstrated that such an angle implies moderate cutting conditions. Interestingly, they also introduced a force index that allows the study of the parameter influence on cutting forces. An example of the influence of the set-up parameters on the cutting parameters is given in Fig. 5, where the values of the instantaneous rake angle α_r for three different shaft angles at the points of the machined gear groove are shown.

Recently, [41] Wang et al. studied the effect of cutter teeth number, relief angle, centre distance, shaft angle and feed motion on the interference between tool and workpiece, and on the machining deviation, which was defined as the difference between theoretical and obtained surfaces. Then, they established an optimization model by taking both interference avoidance and machining efficiency as constraints, and the minimization of machining deviation as objective function. An optimization algorithm based on chaos map was proposed to compute the optimal set of cutting parameters. To verify the effectiveness of their work, experiments were carried out using a workpiece made of plastic.

In his latest work [26], Tapoglou investigated the effect of different feed rate, rake angle and inclination angle values on cutting force components and chip geometry. This allowed the author to draw interesting conclusions on the impact of each parameters on the process. Furthermore, the effect of several cutting strategies with different number of cutting passes and depth of cut was

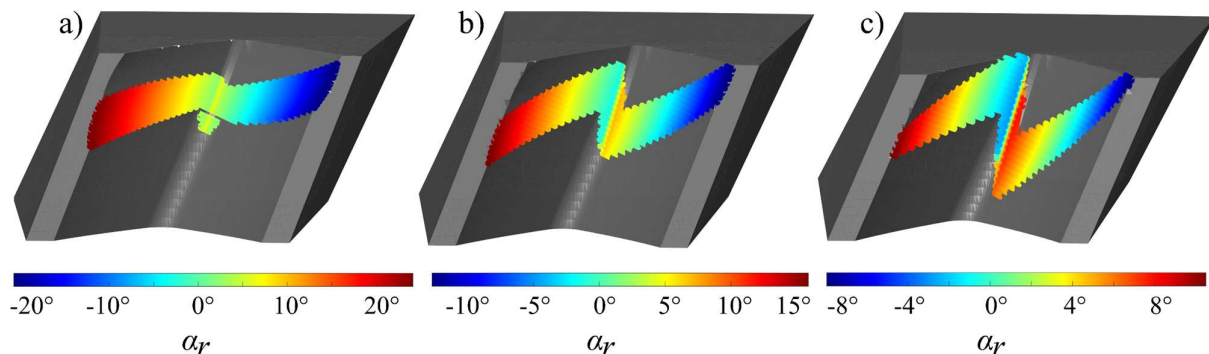


Figure 5: Values of the instantaneous rake angle α_r relative to different shaft angles Σ : a) $\Sigma=7^\circ$, b) $\Sigma=10^\circ$, c) $\Sigma=13^\circ$.

evaluated in the paper. After establishing the calculation model for the UCG, Fang et al. [21] analysed how different radial and feed rates affect the uncut chip shape. In [42], Hilligardt et al. established a geometrical model to evaluate the meshing interference between tool and workpiece. In this study, the authors also estimated the effect of set-up and tool parameters on interference.

As shown, many authors have focused on understanding the cause-effect relationships that determine the cutting parameters. Since the cutting forces and temperatures, thus the tool wear and gear quality, depend on these parameters, the results above can serve as the bases for the development of new tools and cutting strategies.

In section 2.3, it is pointed out that the tool working angles affect the profile error on the cut gear; then, one way to settle this problem is to alter the cutter profile. A viable alternative for decreasing the process cost, is to tune the parameters so as to avoid or reduce gear profile errors. Therefore, many research groups focused their attention on the influence that set-up and tool parameters have on gear quality in terms of profile error and surface roughness. Tachikawa et al. [43] studied the effect of the run out and the pitch deviation on the machined profile of the gear. They built a geometrical model of the problem and validated their study through experiments. In [44], the optimal setting parameters of the machine were computed by constructing a sensitivity matrix and using a linear regression method. For the study, the authors employed a common shaper cutter in order to avoid complicated cutter profile geometries. Furthermore, in a recent study [45], Guo et al. analysed the effect of tool-workpiece position misalignments on tooth profile deviation. In particular, the eccentricity of workpiece and cutter, the tilt error of the cutter and their combined effect were analysed. Afterwards, they verified the consistency of their study with experiments.

In [46], Li et al. studied a parameter selection method to improve the machining accuracy. In particular, they devised a mathematical model of machining errors. By adding constraint conditions that included interference avoidance, addendum thickness minimum limit and top cut avoidance, they were able to select the proper parameter set. This encompassed number of cutter teeth, modification coefficient of meshing gear, rake and relief angle, and feed motion.

In [47], the influence of both rake angle and re-sharpening depth on gear tooth profile errors were thoroughly analysed. Following this, a later work [48] demonstrated the influence of the relative position and orientation between tool and workpiece on profile deviations. Furthermore, the effect of the eccentricity was considered and correlated to the corresponding tooth surface waviness. Similarly, Kiemme et al. [49] studied the teeth micro geometry in relation to run out and tooth number of the tool. The revised articles dealing with the effects of set-up errors on workpiece geometry can be employed both for developing realistic mathematical models of the process and by CNC machine programmers to account for these effects.

Zheng et al. [10] were among the first to investigate the influence of tooth modification parameters on the tooth surface deviation, contact pattern and transmission error. In particular, they analysed three correction methods; namely: centre distance correction, cutter tilted correction and crossed angle correction. In [50], Trübswetter et al. analysed the effect of different axial feeds on gear tooth microstructure, demonstrating a correlation between axial feed and surface waviness. Similarly, in [51] Jia et al. simulated the machined surface topography after the computation of the contact occurring between tool and workpiece surfaces. Recently, Ren et al. investigated the effect of tool eccentricity on gear profile errors [52]. The authors then explored how feed and eccentricity affected surface roughness. To support their study, numerical and experimental trials were conducted. These studies on surface roughness can help developing ad-hoc cutting strategies based on the requested gear quality.

Due to the high cost of cutters, tool durability is a key aspect for the successful application of power skiving. Hence the implication of the parameter variation on the tool wear has been investigated by different scholars.

As mentioned in section 2.1, Guo et al. proposed an oblique cutting model to evaluate the cutting forces [28]. After computing the force density per cutter length at different tool portions, they were able to compare different tool-feed strategies for power skiving. In particular, they compared single feed, multiple side feeds, multiple radial feeds and multiple step feeds. The study revealed that multiple side feeds offer a more homogeneous tool loading and, hence, a better tool wear resistance compared to single and multiple radial feeds. The authors concluded that, though similar to the multiple side feed strategy, the multiple step feed strategy makes the tool recess edge more durable and, therefore, more advisable in power skiving.

In [53], Balabanov et al. investigated the influence of cutting edge radius on tool wear. They compared the results of a simulation with real cutting tests and determined the optimal edge radius for the tool-workpiece pair analysed in the study. In [54], Astashchenko et al. determined the most durable combinations of tool materials and coatings to machine an internal gear made of 38H2MYuA (equivalent to 34CrAlMo5) by power skiving. Interestingly, in [55], Arndt et al. compared dry and wet power skiving using different cutting strategies in terms of both tool wear and gear surface quality. Furthermore, the study was carried out on quenched and tempered 31CrMoV9, with different hardness, and adopting different cutting velocities. The authors concluded that, depending on cutting speed and material hardness, dry gear skiving can extend tool life up to 3 times compared to wet skiving.

To be concise, only the most relevant implications due to parameter variations have been discussed in detail. As in the previous section, Table 2 reports the implications of published papers versus the set of parameters considered. As it can be seen, the implications on cutting parameters and on gear quality are the most addressed. Interestingly, the effect of parameter variation on tool wear has mainly been studied by varying the set-up parameters rather than the tool parameters. Therefore, the influence of tool parameters on tool wear should be addressed in future studies, which may enable the development of novel and more efficient tool designs.

Table 2: Implications analysed by each different paper of the group *parameter influence on the process* versus the set of the considered varied parameters in the paper.

			Cutting parameters			Gear profile and tooth surface quality			Tool wear	Other
Authors	Ref.	Parameters varied	Working angles	Chip	Interference	Profile deviations	Helix deviations	Machining deviations		
Kojima et al.	[34]	$\alpha_r, \beta_t, \Sigma, d, f_a, h_r$	✓			✓				
Chen et al.	[35]	α_r, α_t, f_a			✓					
Li et al.	[36]	$z_t, x_t, \alpha_r, \alpha_t$			✓					
Guo et al.	[37]	Σ, z_t, f_a	✓				✓			
Guo et al.	[38]	Σ, z_t	✓	✓						
Klocke et al.	[12]	Σ, z_t, x_t, δ	✓	✓						Cutting velocity
Tsai et al.	[39]	δ, z_t, x_t	✓							
Moriwaki et al.	[40]	Σ, h_r	✓	✓						
Uriu et al.	[9]	Σ	✓	✓						Cutting velocity
Wang et al.	[41]	$\Sigma, z_t, \alpha_r, f_a, d$			✓			✓		
Tapoglou	[26]	$\Sigma, \alpha_r, f_a, f_r$		✓						Cutting forces
Fang et al.	[21]	f_a, f_r								Tool contact area
Hillgardt et al.	[42]	z_t, SU_{dev}			✓					
Tachikawa et al.	[43]	TS_{dev}				✓	✓			
Guo et al.	[44]	Σ, ω_t, d				✓				
Guo et al.	[45]	SU_{dev}				✓	✓			Workpiece pitch Deviations
Li et al.	[46]	$z_t, \alpha_r, \alpha_t, f_a$			✓			✓		
Guo et al.	[47]	α_r, h_r				✓				
Guo et al.	[48]	$z_t, z_g, f_a, SU_{dev}, TS_{dev}$				✓	✓	✓		
Kimme et al.	[49]	z_t, TS_{dev}						✓		
Zheng et al.	[10]	Σ, δ, d						✓		Transmission-error, TCA
Trübswetter et al.	[50]	f_a						✓		
Jia et al.	[51]	f_r						✓		
Ren et al.	[52]	f_a, TS_{dev}				✓		✓		
Guo et al.	[28]	f_r							✓	Cutting forces
Balabanov et al.	[53]	<i>Tool edge rounding</i>							✓	
Astashchenko et al.	[54]	<i>Tool material and coating</i>							✓	
Arndt et al.	[55]	$f_r, \omega_t, lubrication$	✓						✓	

2.3 Tool design

As in many generative machining processes, in power skiving the tool plays a role of primary importance. Gear teeth are obtained as the envelope of the surface family spanned by the tool teeth while they move relative to the workpiece [8]. Therefore, errors in the tool geometry or in the relative motion will reflect as errors in the geometry of the machined gear.

It is well known from the theory of gearing that the machined gear profile would be error free if the cutter profile is calculated as the intersection between the conjugate surface of the gear to be cut and the rake surface. Many research papers address tool geometry calculation employing conjugate theory, which is one of the pillars in the theory of gearing. For instance, in [56], Xu et al. obtained the tool profile as the intersection between the rake surface and the conjugated surface of the gear to be cut. The authors represented the designed cutter in VERICUT, a CAD environment that allows simulation of cutting action and the observation of the obtained gear geometry. Recently, Jia et al. [57,58] proposed a universal calculation method for the cutting edge involving the envelope for discrete profiles based on conjugate theory to avoid singularities. Simulation was carried out to prove the feasibility of the method.

However, the theoretical tool profile could result as being non-involute, asymmetric and eventually unpractical to produce. Consequently, in industrial practice, it is frequent to find cutters whose profile deviates from the theoretical shape. In addition, in order to facilitate machining, working angles as the rake angle, clearance angle and side relief angle are manufactured on the tool. These can lead to other deviations from the theoretical profile, causing errors on the machined gear profile.

From the literature survey, it appears that investigations in tool design constitute a major topic in power skiving. Several authors focused their attention on novel tool designs that reduce gear errors. In [59], M. Kojima et al. investigated the geometrical relationships between workpiece and cutter. Then, they determined the exact tool profile for cutting an involute gear along with its deviation from an ideal involute. Furthermore, they employed a standard involute shape as the tool profile, and computed the corresponding conjugated gear, showing that this latter presented profile errors. Finally, they proposed a correction of the base circle radius of the tool to reduce such errors. In [60], Chen et al. designed a conical tool with error-free flank faces. The cutting edges at different sharpening depth were obtained as the intersection between a rake face and several conjugated spur gears with different profile-shifting coefficients.

Guo et al. made important contributions in the field of power skiving and published relevant articles concerning tool design. In [5], they computed the cutter profile using conjugate theory, similarly to the approach followed by Jing in [61]. Then, they also presented a novel correction method for the tool profile by altering the pressure angle. In [62], they developed a method to correct the twist of modified tooth flanks by optimizing the cutter profile. In particular, the cutter profile was represented as data points and formulated as a B-spline curve whose correction polynomial coefficients were computed. Polynomial coefficients were also employed in [63], where a new correction method for the tool profile was proposed to obtain an even grinding allowance on the machined gear flanks.

Other articles focused on new tool designs that aim at improving the cutting conditions of the process. In a recent article [38], Guo et al. presented a novel multi-blade cutter. The study encompasses many issues, such as: cutting condition analysis, set-up parameters effects on the process and the investigation of different sub-blade layouts on chip formation. As declared, the novel cutter resembled the one presented by Monden et al. in [64]. The difference lies in the detachable sub-blades that make the cutter easier to regrind. The basic idea of the multiblade cutter is to divide the cutting action, which occurs within a pass, among different sub-blades in order to reduce the load and consequently the wear on the tool profile. In [65], Monden et al. demonstrated that machining a 200 HB steel with a multi-blade cutter reduced the tool wear by six times compared to a normal skiving cutter. However, they also highlighted that the difference in tool duration decreased rapidly as the workpiece hardness was increased. In [66], a novel interference-based tool design technique was proposed that accounts for the possibility of interferences during rough and semi-finishing passes.

Another highly studied issue inherent of skiving tools lies in the re-sharpening process and its influence on the tool profile. As mentioned in the previous section, tools can be either cylindrical or conical. The latter strongly resembles corrected involute gears since they have tapered teeth along the face width due to the employment of clearance and side relief angles. Since cylindrical cutters are likely to lead to negative clearance angles in skiving application [39], conical cutters appear to be more popular. Furthermore, their employment simplifies the setup and offers better tool wear resistance [67]. However, due to the lack of an appropriate change in cutter profiles along the face-width, their re-sharpening process could increase profile deviations of cut gears. In contrast, cylindrical cutters remain unaffected by re-sharpening because of their unchanging cross section.

By linking the rack profile shifting coefficient with the re-sharpening depth, a novel tool design that improves the instantaneous clearance angle values was presented in [39]. After calculation of clearance angles, the authors designed the tool flank surface using a continuously changing cross section in which the profile shifting coefficient varied along the tool width. By doing so, the clearance angle values improved and the advantage in re-sharpening, typical of cylindrical tools, was retained. Interestingly, the authors also calculated a limit depth for re-sharpening after which the values of instantaneous clearance angle became negative and, thus, unacceptable. In a recent work [68], Tsai devised a novel design method for cylindrical skiving tools based on a rake-surface offset. This allows the employment of cylindrical cutters and their inherent advantage on re-sharpening, while avoiding clearance angle to reach negative values.

Shih et al. [67] devised an error free conical cutter. They obtained the tool flank face cutting edges from the intersection curves of the rake face and a set of generating gears. These were derived as conjugates of the work gear using progressively decreasing profile shifted coefficients to account for re-sharpening. Furthermore, in [69], they proposed an error-free cylindrical skiving tool for machining the circular spline of harmonic drives. The proposed design is based on a rake-surface offset similar to [68].

In [7], Wang et al. presented an error free tool design for machining cycloidal gears considering re-sharpening. To assess the feasibility of the design, the authors carried out a process simulation employing VERICUT and by machining a plastic gear. In [70,71], the same research group devised a novel cutter for a rotate vector reducer with circular arc teeth. After a process analysis, the authors compared a planar rake face with a curved one in terms of instantaneous rake angle and cutting forces. The results showed that the curved rake face has a more reasonable cutting angle and a better cutting performance. In addition, Wang et al. [72] recently proposed a novel design method for skiving cutters based on conjugated surfaces. This method allowed the computation of the error free profile and, afterward, the selection of a free form rake face that improves cutting conditions.

In the works reported in this section, many authors claimed error-free tool designs; however, these designs resulted not applicable in practice. Hence, the potential of many of the proposed tool designs remains currently unexploitable. For each paper, Table 3 reports the targets aimed by the proposed tool design.

2.4 Miscellaneous

Due to the grouping method adopted in this paper, some articles have not been included in the three groups reported above. These papers are considered in this miscellaneous section. They aim at solving other, so far less investigated, power skiving issues.

In particular, in [73], Chen et al. presented a grinding method for the flank faces of an error-free spur slice cutter. The geometrical characteristics of the flank faces were analysed. Then, the grinding motion model based on a five axis CNC machine tool for grinding was developed, the proposed grinding method was applied in practice for its validation and the required machining accuracy was obtained.

A different study was carried out by Tsai et al., who proposed a methodology for the generation of the NC code required to manufacture gears by power skiving on a conventional six-axis CNC turn-mill machining centre [74]. The authors emphasized that the quality of gears produced by power skiving using dedicated machine tools is obviously better than that produced using conventional six axis machine tools. In particular, the machining accuracy that was reached in the experimental trial was insufficient for practical applications. However, this study represented a first step toward the employment of power skiving process in general purpose CNC machines.

Tachikawa et al. [75] were the first to direct their interest toward the complex problem of vibrations in power skiving. They proposed a simple method to compute the time series of cutting forces, considering the simultaneous mesh of multiple cutting edges. After establishing a mathematical model for the cutting forces power spectrum, the authors estimated the frequency at which these fluctuated. Considering the natural frequencies of the cutter and the clamped workpiece, they predicted the rotational speed of the cutter that was most likely to reduce vibrations. Experimental measurements with acceleration sensors were also carried out and compared with simulated results, showing the effectiveness of the method.

Interestingly, Nagata et al. [76] successfully converted the production from shaping to skiving of an internal gear batch. In [17], Nishikawa et al. developed a power skiving machining facility for mass production and provided a clear overview of the process. Fularski et al. [77] experimentally demonstrated that chips welded or bonded to the gear tooth surfaces after gear skiving can adversely affect the ensuing hardening process. Trübswetter et al. compared the effect of different hard finishing processes (namely, generating grinding, polish grinding and gear skiving) on the surface structure of a case hardened 16MnCr5 gear [78]. In their study, the excitation behaviour was investigated experimentally. In [22], Ren et al. investigated the correlation between local cutting parameters and the surface integrity of the machined gear flanks. In this study the deformation level and microstructural alterations of the access and recess gear flanks were gauged. The authors gave a rational explanation of the greater deformation on the recess flank. Then, recently, Han et al. applied the power skiving process for machining face gears [79]. Table 4 summarises the topics addressed by each paper considered in this section.

Table 3: Targets aimed at being improved by the tool designs proposed in the third group of examined papers.

Authors	Ref.	Gear profile error reduction	Tool resharpener optimisation	Cutting conditions improvement
Kojima et al.	[59]	✓		
Chen et al.	[60]	✓		
Guo et al.	[5]	✓		
Guo et al.	[62]			✓
Guo et al.	[37]	✓		
Luu et al.	[63]	✓		
Monden et al.	[64]			✓
Monden et al.	[65]			✓
Fang et al.	[66]			✓
Tsai et al.	[39]		✓	✓
Tsai et al.	[68]		✓	✓
Shih et al.	[67]	✓	✓	✓
Shih et al.	[69]		✓	✓
Wang et al.	[7]	✓	✓	
Wang et al.	[70]	✓	✓	
Wang et al.	[71]	✓	✓	✓
Wang et al.	[72]	✓	✓	

Table 4: Topics addressed in the miscellaneous group of the examined articles.

Authors	Ref.	Topic
Chen et al.	[73]	Grinding method for spur cutters
Tsai et al.	[74]	NC code generation to perform power skiving on a 6 axis CNC machine
Tachikawa et al.	[75]	Vibrations reduction in power skiving
Nagata et al.	[76]	Change of batch production from shaping to power skiving
Nishikawa et al.	[17]	Development of a power skiving facility for mass production
Fularski et al.	[77]	Experimental study on the effect that chips welded to the gear surface after skiving, have on the ensuing case hardening process
Trubswatter et al.	[78]	Comparison of the effect that different hard finishing processes among which skiving, have on the machined surface structure
Ren et al.	[22]	Surface integrity of gear flank in gear skiving
Han et al.	[79]	Power skiving of face gears

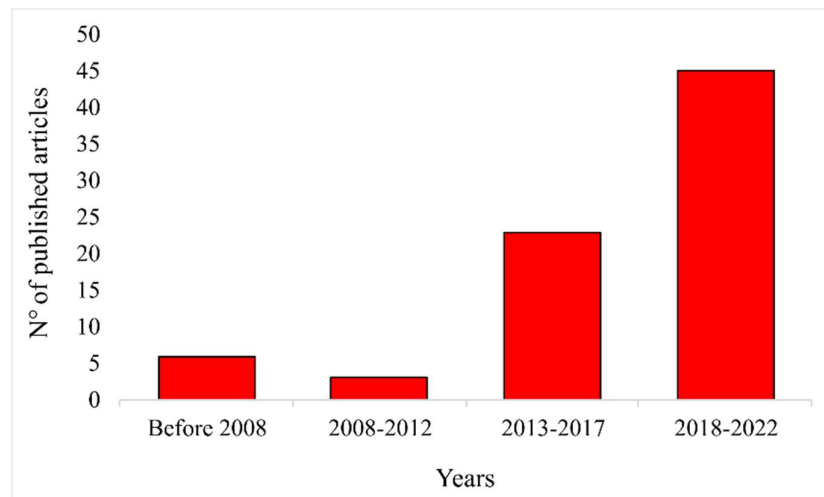
3 Discussion

In this section a synthetic comparison between the reported articles belonging to the different groups is presented firstly. Then, study deficiencies in the field of power skiving along with practical limitations, which hinder practical developments, are underlined. Afterwards, possible new research directions in this field are discussed.

As already mentioned, the gear quality and the cutting conditions result to be the more relevant issues for the process. As a result, these issues constitute a common thread among the groups. Indeed, the key factors simulated in the first group, are those whose variations are studied in the second group. The two main issues are also found in articles of the third group, since the efficiency of new tool designs is based on them. The different groups are related to each another and all of them are relevant in the field. Therefore, none of them can be regarded as prevailing on the others. However, the following considerations can be highlighted.

Articles belonging to the first group propose new ways to compute key factors of the process. It is crucial for the development of this technology that more studies of this type are pursued. This will allow more efficient calculations improving the ones discussed in section 2.1 and the implementation of more complex mathematical models. The articles of the second group dealt with the concepts that may lead to the development of novel cutting strategies and new tool designs. Therefore, they will play the main role in future research. As regards the articles of the third group, despite the relevant breakthroughs accomplished to date, many of the proposed tool designs are neither practical to produce nor to re-sharp. It is advisable that if new tool designs will be proposed, their practical realization should be considered as well in the design phase. The miscellaneous group that currently includes few articles must be enlarged with innovative studies which will help to gather new understandings of the process.

As regards study deficiencies, it should be stressed that power skiving has only been effectively employed in gear manufacturing companies since the last decade. This determines a general shortage in scientific publications on power skiving. Compared with other gear machining processes like hobbing and shaping, only a few studies have been conducted to date. However, from Fig. 6, which shows the rate of publications on power skiving over the years, it can be inferred that several new studies will be published in the near future. It is hence plausible that many of the topics highlighted in the following will be exhaustively covered as well.

**Figure 6:** Publications over years.

In many machining processes, a crucial role is played by the local temperature which develops in the cutting zone. In power skiving, this zone is very small and, hence, the temperature increase due to the cutting action is highly localized. This phenomenon heavily affects the chip evacuation, since chips could weld to the teeth surface, jeopardising the workpiece surface quality. However, as described in [4,55], the developed heat decreases the resistance against deformation of the chip in the shear zone and this softening effect can reduce cutting forces along with tool loading and wear. As presented in section 2.1, few research groups [11,18,31] focused on the local temperature of the cutting area. Despite the interesting results obtained, new research should be carried out in this direction. Similarly, the phenomenon of tool wear needs further investigation. Indeed, Table 1 showed that only a few studies on tool wear have been conducted so far, whereas Table 2 revealed that there is a lack of studies directly relating tool design parameters to tool wear. This could bring new insights not only on the process but also on tool design. The full comprehension of the temperature-rise phenomenon and of the tool wear mechanism could assist in the development of strategies that provide better stability to the process.

A similar reasoning could be applied to mechanical vibrations. As power skiving is characterized by harmonic forces, when their periodicity coincides with one of the machine-workpiece natural frequencies, the system exhibits resonance behaviours. Unfortunately, this is not the only issue. As reported in [80], self-excited chatter vibrations are the most detrimental for the safety and quality of machining operations. Machine tool chatter vibrations result from a self-excitation mechanism in the generation of chip thickness during machining. This happens when one of the structural modes of the machine tool-workpiece system is initially excited by cutting forces. As a consequence, a wavy surface finish, left during the previous pass, is removed during the succeeding tooth period which, in turn, leaves a wavy surface owing to structural vibrations [81]. Depending on the phase shift between the two successive waves, the maximum chip thickness may grow exponentially while oscillating at a chatter frequency that is close to a dominant structural mode in the system. The growing vibrations increase the cutting forces and may fragment the tool and produce a poor, wavy surface finish. Tachikawa et al. [43] only addressed the forced vibration problem, whereas the effects of chatter in power skiving have not been investigated yet. Hence, new studies on this topic should be conducted.

Another key aspect, which has not been sufficiently addressed in literature, is how different tool rake surface structures affect the process. This parameter heavily influences the friction behaviour in the cutting zone and, consequently, on the chip evacuation that is strictly linked with the stability of the process.

Moreover, from the articles presented in previous sections, a gap emerges concerning investigations on the influence that different materials may have on power skiving. There is a lack of scientific publications similar to [54] that study how different tool materials and coatings behave with different workpiece materials. This lack can be associated to two phenomena constituting the biggest limitations in power skiving experimental trials. First, the cost of machines and tools: in order to carry out the process properly, special purpose skiving machines should be used, whose cost is remarkably high. Furthermore, testing any kind of parameter variations in the process opens the possibility to tool damage, whose cost cannot be neglected. As a result, many research groups carry out collaborations with industries, which employ the power skiving process and want to improve their production efficiency through a better understanding of the technology. This brings about the second major limitation, which is the companies' confidentiality maintenance. Since corporations want to protect their know-how from competitors, it is likely that findings resulting from fruitful collaborations have not been published yet. Despite this, it is expected that with the advancement of the technology, information now considered confidential will soon enter into the public domain.

Since the effect of each parameter on the process is not completely understood, in the published articles there is a tendency to vary one parameter at a time. However, multi parameter variations could allow the disclosure of novel cutting strategies.

Moreover, many factors have not yet been taken into account in process simulations; in particular: the effect of different lubrication methods as well as of tool and workpiece flexibility. By considering all these aspects, more accurate models will be achieved, allowing higher process stability and its further optimisation.

This, in turn, could facilitate the practice of hard power skiving. Like most gear cutting procedures, power skiving is followed by a hardening heat treatment of the surface of the component. However, in rare cases power skiving is applied, as a finishing process [82], on pre-machined parts that have been already hardened. In this case the process is labelled as hard power skiving. This puts skiving in comparison with grinding [78]. Despite the novel process results faster, the extreme tool wear makes its use on hardened gears highly unstable. Such an instability is associated not only with the high hardness of the workpiece, but also with the deformations caused by heat treatment, such as run-out or helix deviations. The deformations may trigger vibrations during machining which, in turn, can cause an early tool wear. It is believed that, once a thorough understanding of this cutting method is reached and the process is optimized, hard power skiving will gain greater stability and its use will spread further.

Fig. 7 summarizes the content of this review. The efforts made by researchers to date, though carried out in different ways, aimed at improving the process in terms of gear quality and by reducing the wear, hence enhancing the cutting conditions. With the advances made to date, power skiving has become competitive and even preferable to traditional gear machining technologies. However, by further investigating the discussed topics, the process could be exploited to its full potential and could be considered as an all-in-one process able to compete also with finishing processes. Consequently, it cannot be excluded that in the next decades, companies will renew their machinery primarily with power skiving equipment rather than with traditional cutting machines.

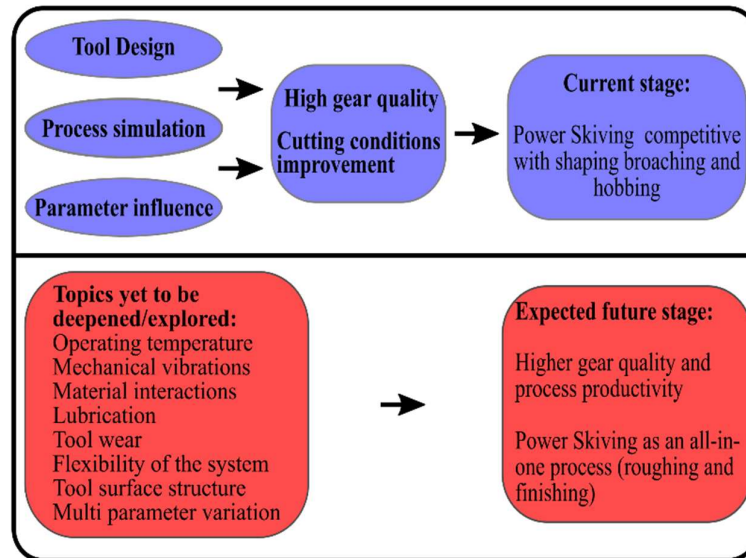


Figure 7: Current and predicted state of the art of Power Skiving.

Conclusions

In this article, a comprehensive review on the state of the art of power skiving process has been presented. The scientific papers published to date and related to the process have been analysed and classified in groups according to their content. Four groups emerged from this study that have been named as: i) *cutting process principle and simulation*, ii) *parameter influence on the process*, iii) *tool design* and iv) *miscellaneous*. The survey has been conducted by considering the gear quality and the cutting conditions, which determine the tool wear, as the key issues of the power skiving process. Each group has been presented along with the corresponding relevant publications and treated topics, which have been critically discussed highlighting literature deficiencies and possible new research directions. A table for each group has been reported that synthesizes the main contributions of the articles to the power skiving process.

The study showed that both the phenomenon of tool wear and the related aspects as the operating temperature need further investigations in order to improve the process stability. This article fills a gap in the literature by both providing the state of the art of the power skiving process and offering a useful reference to researchers and practitioners in this field.

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