Jun. 2022 Transactions of Nanjing University of Aeronautics and Astronautics Vol. 39 No. 3

Simulation Study on Influence of Rake Angle in Gear Skiving Processes

REN Zongwei, *FANG Zhenglong**

Department of Mechanical Engineering, Graduate School of Engineering, the University of Tokyo, Tokyo 113-8656, Japan

(Received 21 April 2022; revised 1 June 2022; accepted 10 June 2022)

Abstract: Gear skiving is a promising gear cutting technology that can achieve a multiple faster internal gear cutting process than that of gear shaping. However, the kinematic system complicates skiving process, resulting in severe crater wear due to the intense variation of local cutting features. In particular, the negative rake angle near the cut-out is recognized as influential factor affecting the cutter wear progress, which needs the sophisticated simulation approach to elucidate the underlying cutting mechanism. In this research, the influence of the rake angle, e.g. top and side nominal rake angles of the cutter, is studied to further understand its role in the gear skiving process, for seeking the possibility of skiving process improvement by calculating the effective rake angle. As a result, the top and side rake angles of the cutter can both increase the effective rake angle when compared with the case of the none-rake angle, leading to an enhanced skiving process. This work provides fundamental knowledge of the rake angle for the gear skiving research, contributing to the optimization on the cutter parameters by considering the effective rake angle.

Key words: gear skiving; numerical simulation; parametric modeling; cutting characteristics; cutter geometries

CLC number: TH132 **Document code:** A **Article ID:** 1005-1120(2022)03-0263-08

0 Introduction

Gear skiving is a promising gear cutting technology with high productivity and accuracy, especially for internal gear. However, the high wear rate of cutters has been a barrier to its implementation in the past decades[1]. Recently, with the development of electrical gearbox function and rigid of machine tools as well as tool coating technology, gear skiving has been treated as the contemporary gear solutions technology as a powerful alternative to the gear shaping a hobbing in both internal and external gear teeth manufacturing[2]. Therefore, comprehensive clarification and understanding of the mechanism of gear skiving process is urgent to support the arising industrial application.

Due to the complex cutting environment in gear skiving, a direct observation on cutting process is difficult. Hence, various of simulation technologies have been developed for visualization of the cutting process, which is especially helpful for understanding the gear generation process and improving the gear skiving performance. Among the targets of simulation, uncut chip geometry (UCG) is one of the most effective ways for visual display of the cutting process[3-4]. Cutting characteristic, e. g., rake angle and uncut chip thickness, could further help for comprehensive understanding the cutting process. To the date, computer aided design (CAD) or CAD-based approach[5-7] and numerical calculation approach[8-10] were developed with the skiving process clarification. The above approaches are effective in generation 2- and 3-dimensional UCG and calculation of cutting characteristics. Based on the cutting characteristics rendered UCG, the features of gear skiving process, such as variation of rake an-

---

*Corresponding author, E-mail address: fangzhl@hnl.t.u-tokyo.ac.jp.

How to cite this article: REN Zongwei, FANG Zhenglong. Simulation study on influence of rake angle in gear skiving processes[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2022, 39(3): 263-270.

http://dx.doi.org/10.16356/j.1005-1120.2022.03.001

gle could be displayed, providing an effective tool for the studies on the kinematic, cutting and cutter parameters[6,11-13].

The kinematic characteristics of the gear skiving lead to an intense local cutting feature variation during a single-cut from the approach to the recess flank. In particular, the rake angle experiences a change from the positive to the negative during the skiving process, leading to an unappreciated skiving condition subjected to the rake face. Nominal side and top rakes are two cutter parameters that can change the local effective rake angle. By simulating the variation of cutting characteristics with different cutter geometry conditions, the influences of the rake angle could be clarified[14], enabling an improvement on the gear skiving process as well as the cutter design.

In this paper, we investigated the influence of the rake angle to the skiving process by conducting the simulation assessment on the local effective rake angle. Specifically, two critical cutter rake angles were investigated, e.g. top and side rake angles, associated with the skiving process clarification by projecting the effective rake angle to the UCG in the parametric space, enabling the improvement on the cutter design and process assessment. Other statue variable aside effective rake angle can be transferred to the assessment by following the research route of this work. The reminder of this paper is constructed as follows: Section 1 presents the basic knowledge and kinematic of gear skiving, i.e., the configuration of the cutter and the workpiece, and the infeed technology. Section 2 presents the simulation result of skiving process based on the given cutting edge profile and cutting conditions. The influences of a part of cutter geometries are given in Section 3, followed by discussion and concluding remarks summarized in Section 4.

1 Gear Skiving Process

For a given set of gearing, gear skiving system is consisted of the cutter and kinematic parameters, which are critical for determining the cutting performance[15-18]. Fig.1 presents the configuration of a typical internal gear skiving. The taper angle is attached to the pinion cutter, also named as conical cutter, to avoid the interference between the cutter flank and the tooth gap, which is due to the kinematic nature of the meshing motion of gear skiving kinematic. Basic elements of the kinematic system include the inclination angle and the tile angle (or sometimes uses offset angle), for generating the cutting velocity during meshing and interference-free adjustment, respectively. In particular, both the tilt angle[1,16] and the offset angle are helpful for reducing the interference risk in skiving process, as shown in Fig.1, but are generally applicable to different scenarios, i.e., the tilt angle is for conical cutter and the offset angle is for cylindrical cutter.

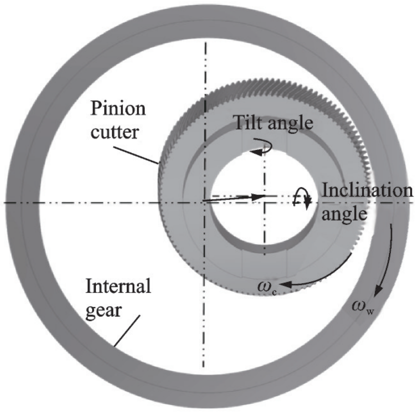


Fig.1 Configuration of internal gear skiving

The rotation speed relationship between the cutter and the workpiece when the cutter provides the incremental movement is as follows[15]

$$w_w = \frac{Z_c}{Z_w} w_c - \frac{2v_a \sin\beta_w}{m_n Z_w} \tag{1}$$

where v_a is the axial feed speed; Z_c and Z_w are the tooth numbers of the cutter and the workpiece, respectively; and β_w is the helix angle of the workpiece. The gear skiving process requires attentive experimental trails for a moderate cutting performance. Therefore, an effective numerical simulation approach was proposed to visualize the cutting process and quantify the cutting characteristics.

2 Simulation Process

The numerical simulation is applied to obtain the cutting process and results based on a given set of cutter, gear and cutting conditions. Fig.2 shows the flowchart of simulation process, which is integrated into our in-house developed gear skiving simulation software, enabling us to obtain the local cutting feature and parameter optimization. The cutting edge sweep surface could be obtained based on the cutter geometries and cutting conditions including module, tooth number, infeed, etc. The calculation was carried out based on the two adjacent sweep surfaces. The output of simulation approach includes the UCG, rake angle, uncut chip thickness, as well as the parameters indicating the workpiece quality, such as the surface roughness. In addition, based on the simulation output, the cutter geometries or cutting conditions could be redesigned for achieving a better cutting performance.

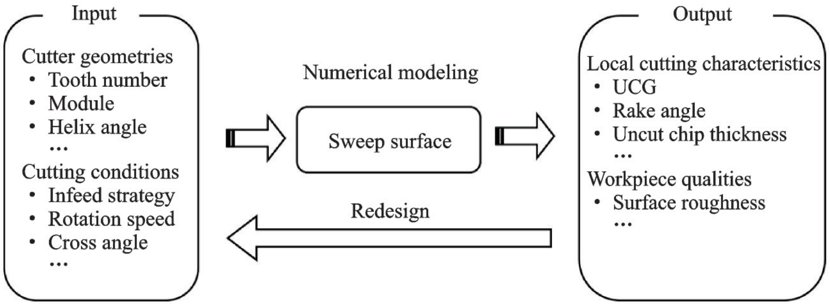


Fig.2 Flowchart of the proposed simulation approach

2.1 Theory and modeling

The modeling method of the sweep surface and other cutting characteristics are presented as follows. Firstly, the cutting edge could be parameterized for detailed understanding of cutting process as follows

$$P(u)=[x_p(u), y_p(u), z_p(u), 1]^{\mathrm{T}} \qquad (2)$$

where $u \in I_u = [0, 1]$. The workpiece is assumed to be fixed and the sweep surface resulting from the relative motion of the cutting edge on the workpiece can be expressed by the following equation

$$S(u,w)=[T(\theta), P(u)]^{\mathrm{T}}+G(w) \qquad (3)$$

where $w \in I_w = [0, 1]$. T is the homogeneous rotation matrix and $G(w)$ the trajectory of S. Parameter θ is the function of the parameter w that defined by the kinematic motion of the skiving process. When the simulated tooth gap of the gear rotates back to the simulation position, the cutting is performed with axial infeed movement, which needs to be noted that the cutting may not be strictly conducted by the same tooth of the cutter but is determined the gear ratio. This fact is important for understanding the underlying mechanism of the eccentricity error of the cutter on the surface formation.

The gear skiving is featured with the evolving cutting conditions during a single-cut, e.g., effective rake angle, uncut chip thickness, and clearance angle. Therefore, UCG is of great importance for comprehensive understanding the cutting processes. Generally, the local cutting feature varies with the meshing moment during a single-cut. Oblique cutting model was used to derive the cutting feature from the differential cutting edge[9].

2.2 Case study

A case study was carried out based on the above modeling process. A tapered cutter with involute tooth profile was employed to process an internal spur gear. The module of the cutter is 2 mm and the tooth number is 25. Detail parameters are listed in Table 1. Two rough passes and one finishing pass were conducted to complete the whole gear gap.

Fig.3 presents the calculated sweep surface in Cartesian coordinate system based on the cutting edge and the cutting conditions of the 1st pass. A curved cutting trajectory of the center point of the

Table 1 Cutter geometries and cutting conditions

Parameter	Value
Cutter module/mm	2
Tooth number	25
Helix angle/(°)	20
Top rake angle/(°)	0
Side rake angle/(°)	10
Pressure angle/(°)	20
Modification coefficient	0
Rotation speed/(r•min^{-1})	1 000
Axial feed/(mm•r^{-1})	0.2
Cross angle/(°)	20
Offset angle/(°)	0
Tile angle/(°)	0
Radial feed: The 1st pass/mm	2
Radial feed: The 2nd pass/mm	1.8
Radial feed: The 3rd pass/mm	0.2

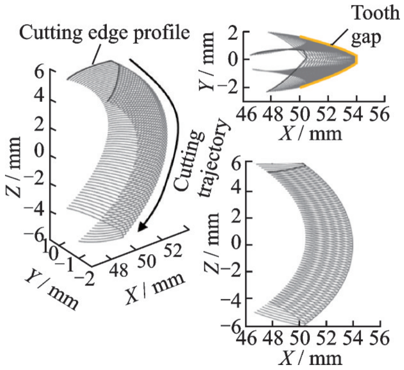
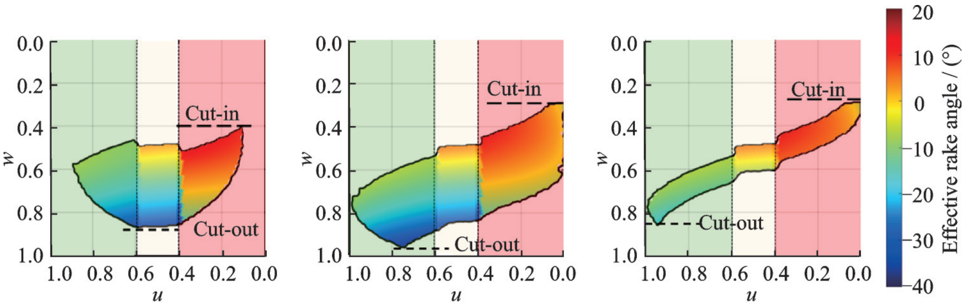


Fig.3 Sweep surface of the 1st pass

cutting edge is formed. The generated gear gap could be clearly seen from X-Y view. By employing the cloud-based Z-map method[9] or a level counter method[19], the gear gap on the workpiece and UCG could be obtained. Here, the Z-map method was employed to illustrate the result. The X-axis values on the sweep surface and the workpiece were compared. The meshing size is 40 μm × 40 μm. Noted that, the finite element model based numerical calculation is not applied to this work since the geometrical feature related the skiving process alteration is concerned.

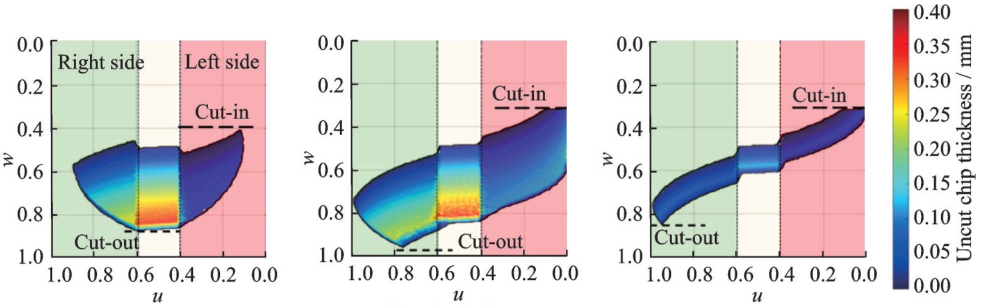
Figs.4 and 5 show UCGs of three passes rendered by the effective rake angles and the uncut chip thicknesses, respectively, depicted in the parametric space for better understanding the cutting characteristics on the cutting edge. The horizontal axis of Figs. 4, 5 is the parameter u of the cutting edge, while the vertical axis indicates the trajectory parameter of w, which could be regarded as the cutting time. Color coding is conducted to indicate the part of the cutting edge, i. e., cutting edge on right flank, tooth top, and left flank, respectively. For the effective rake angle, all three passes show the same trend that the effective rake angle decrease from cut-in to cut-out. In three different passes, it could be seen that as the later of cut-out, i.e., the larger of w, the smaller rake angle becomes, indicating a better cutting performance when the cutting finished earlier. The obvious boundary between the different color blocks is caused by the discontinuous of the cutting edge at the tooth top and flanks. Therefore, a continuous curve could reduce abrupt variation of cutting conditions between the tooth flanks and tooth top.

As for the uncut chip thickness, it is far less than the infeed amount in the 1st pass and the 2nd pass. This may indicate that a smaller value of radial and axial in feed dominates the main of the uncut chip thickness. The results reveal that which part of



(a) The 1st pass (b) The 2nd pass (c) The 3rd pass

Fig.4 Effective rake angles subjected to UCG in parameter space



(a) The 1st pass (b) The 2nd pass (c) The 3rd pass

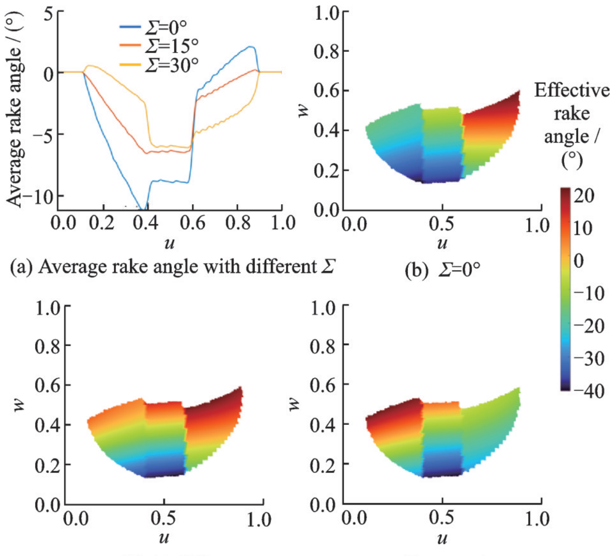
Fig.5 Uncut chip thicknesses subjected to UCG in parameter space

the cutting edge is involved in the cutting process and more prone to wear. In the current cutter geometries and cutting conditions, the larger uncut chip thickness indicates that the tool wear is remarkable in the tooth top and the flank is around $u = 0.6$. Similar with that in effective rake angle, the discontinues of the uncut chip thickness at $u = 0.4$ and $u = 0.6$ are caused by the discontinues of the cutting edge. In addition, combining with the effective rake angle result, the uncut chip thickness is large while the effective rake angle is negative in cut-out, indicating the poor cutting conditions. In sum, the right side of the cutting edge can be considered as being subjected to a severe skiving process, resulting in a faster wear rate.

Moreover, based on the above results, the main cutting characteristics affecting the cutting performance could be researched on the cutting edge. Therefore, based on the distribution of cutting characteristics, the improvement of the cutting performance could be achieved by redesigning the cutter geometries or the cutting conditions.

3 Influence of Nominal Rake Angle

Fig.6 shows the influence of the side rake angle (Σ) on distribution of the effective rake angle, where the side rake angle is set as 0°, 15°, and 30°, respectively. The top rake angle is 0°, and the other conditions are the same as those in Table 1. The minimum effective rake of the tooth top, i.e., $u = 0.4$—0.6, increases slightly while the other part of the cutting edge improves greatly. Especially, the effective rake angle on the right cutting edge, i.e., $u < 0.4$, is larger than that on the left cutting edge, i.e., $u > 0.6$, in Fig.6(b); however, it becomes smaller than that in Fig.6(d), showing the existence of a value that balances both sides of the cutting-edge. The result reveals that the side rake angle is a critical parameter for determination of the effective rake angle. The side rake angle between 15°—30° shows balanced effective rake angle distribution on UCG, indicating a better cutting performance. However, the lower limit of the effective rake angle on the tooth bottom is difficult to be changed.

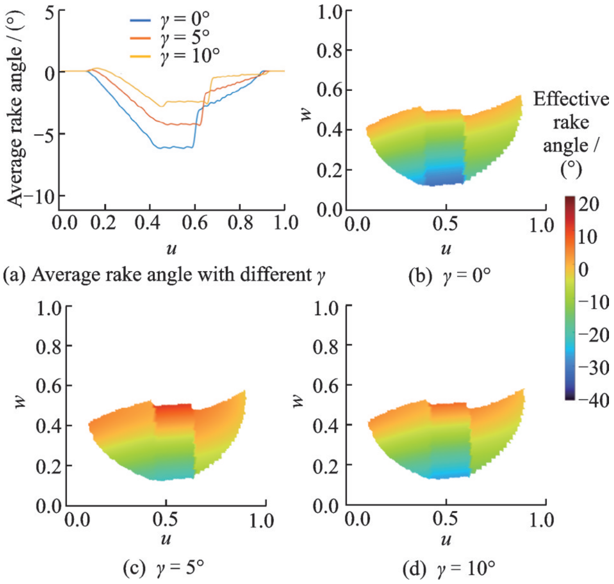


(a) Average rake angle with different Σ (b) Σ=0°

(c) Σ=15° (d) Σ=30°

Fig.6 Distribution of effective rake angle on UCG of the1st pass with different side rake angles Σ

Fig.7 shows the influence of the top rake angle (γ) on the distribution of the effective rake angle. The top rake angle of the cutter is set as 0°, 5°, and 10°, respectively. The side rake angle is set as 20° according to the above discussion. The other conditions are the same as those in Table 1. With the increase of the top rake angle, the effective rake angle in the cutting process also becomes larger overall, indicating large top rake angle is helpful for improvement the poor cutting conditions at the cut-out position.



(a) Average rake angle with different γ (b) γ = 0°

(c) γ = 5° (d) γ = 10°

Fig.7 Distribution of effective rake angle on UCG of the 1st pass with different top rake angles γ

4 Conclusions

Based on the above discussion, the effective rake angle distribution could be improved by employing the proper top rake angle and the side rake angle. Especially higher top rake angle could make the effective rake angle positive at the positive of cut-out. However, the larger top rake angle will decrease the strength of the tip of the cutter. Therefore, threshold of the cutting force should be considered as the limitation of the top rake angle.

In gear skiving, both the UCG and cutting characteristics depend highly on the initial cutter geometries and cutting conditions. Due to the various parameters, it is difficult to derive a universal conclusion of cutter geometries or cutting conditions for high skiving performance. Therefore, a convenient, easy-to-understand, and universal simulation approach is especially helpful for verifying the cutting process and improving the cutting performance in practice. In this research, a systematic modeling process of gear skiving was introduced. For given cutter geometries and cutting conditions, parametric modeling of the cutting edge and cutting conditions were applied to obtain UCGs and cutting characteristics. The cutting characteristics rendered UCGs present clearly the cutting process, which helps engineer or researchers make a comprehensive understanding and improvement on the skiving process.

Moreover, an increase of the top rake angle may bring the tool tip strength concern, meaning the improvement on the local rake angle needs to consider the possible cutter failure type, i.e. chipping, to balance the rake angle incasement and the cutter strength, as shown in Figs.6 and 7, a sudden rake angle variation (about $u = 0.6$) could lead to the force concentration, resulting in the chipping phenomenon even the rest of the cutting edge still remains integrity.

The concluding remarks for delivering the transferrable knowledge are summarized as follows:

(1) The parametric modeling process on the gear profile and the skiving process are effective for obtaining the UCGs and cutting characteristics.

(2) The effective rake angle on different parts of the cutting edge shows decreasing trend. The negative effective rake angle in the cutting out is an unfavorable result.

(3) The uncut chip thickness is zero from the cut-in position and increases gradually to the cut-out position, indicating a upward milling liked the cutting process.

(4) The influences of part of cutter geometries on the effective rake angle in the cutting process are clarified by using different rake angles and side rake angles of the cutter.

References

[1] STADTFELD H J. Power skiving of cylindrical gears on different machine platforms[J]. Gear Technology, 2014, 31(1): 52-62.

[2] KOBIALKA C. Contemporary gear pre-machining solutions[J]. Gear Solutions, 2013, 11(4): 42-49.

[3] FROMENTIN G, POULACHON G. Geometrical analysis of thread milling—Part 2: Calculation of uncut

chip thickness[J]. The International Journal of Advanced Manufacturing Technology, 2010, 49(1): 81-87.

[4] KARAGÜZEL U, UYSAL E, BUDAK E, et al. Analytical modeling of turn-milling process geometry, kinematics and mechanics[J]. International Journal of Machine Tools and Manufacture, 2015, 91: 24-33.

[5] ANTONIADIS A. Gear skiving—CAD simulation approach[J]. Computer-Aided Design, 2012, 44(7): 611-616.

[6] TAPOGLOU N. Development of cutting force model and process maps for power skiving using CAD-based modelling[J]. Machines, 2021. DOI: 10.3390/machines9050095.

[7] TAPOGLOU N. Calculation of non-deformed chip and gear geometry in power skiving using a CAD-based simulation[J]. The International Journal of Advanced Manufacturing Technology, 2019, 100(5): 1779-1785.

[8] JIA K, GUO J, MA T, et al. Mathematical modelling of power skiving for general profile based on numerical enveloping[J]. The International Journal of Advanced Manufacturing Technology, 2021, 116(1): 733-746.

[9] REN Z, FANG Z, ARAKANE T, et al. Parametric modeling of uncut chip geometry for predicting crater wear in gear skiving[J]. Journal of Materials Processing Technology, 2020. DOI: 10.1016/j. jmatprotec.2020.116973.

[10] MORIWAKI I, OSAFUNE T, NAKAMURA M, et al. Cutting tool parameters of cylindrical skiving cutter with sharpening angle for internal gears[J]. Journal of Mechanical Design, 2017. DOI:10.1115/1.4035432.

[11] VARGAS B, ZAPF M, KLOSE J, et al. Numerical modelling of cutting forces in gear skiving[J]. Procedia CIRP, 2019, 82: 455-460.

[12] MCCLOSKEY P, KATZ A, BERGLIND L, et al. Chip geometry and cutting forces in gear power skiving[J]. CIRP Annals—Manufacturing Technology, 2019, 68(1): 109-112.

[13] ONOZUKA H, TAYAMA F, HUANG Y, et al. Cutting force model for power skiving of internal gear[J]. Journal of Manufacturing Processes, 2020. DOI:10.1016/j.jmapro.2020.04.022.

[14] URIU K, OSAFUNE T, MURAKAMI T, et al. Effects of shaft angle on cutting tool parameters in internal gear skiving[J]. Journal of Mechanical Science and Technology, 2017, 31(12): 5665-5673.

[15] GUO E, HONG R, HUANG X, et al. Research on the design of skiving tool for machining involute gears[J]. Journal of Mechanical Science and Technology, 2014, 28(12): 5107-5115.

[16] TSAI C Y. Mathematical model for design and analysis of power skiving tool for involute gear cutting[J]. Mechanism and Machine Theory, 2016, 101: 195-208.

[17] MONDEN T, KIKUCHI T, CHIHARA Y, et al. MHI super-skiving system for longer tool life and enhanced efficiency in internal gear cutting[J]. Mitsubishi Heavy Industries Technical Review, 2015, 52(1): 101-105.

[18] GUO E, HONG R, HUANG X, et al. A novel power skiving method using the common shaper cutter[J]. The International Journal of Advanced Manufacturing Technology, 2016, 83(1): 157-165.

[19] FANG Z, REN Z, KIZAKI T, et al. Construction of uncut chip geometry in gear skiving using level contours[J]. Precision Engineering, 2022, 73: 93-103.

Authors Dr. **REN Zongwei** received the B.S. degree in mechanical engineering from Dalian University of Technology in 2008, the M.S. degree in mechanical engineering from Tohoku University, Japan and the Ph.D. degree in mechanical engineering from the University of Tokyo in 2021, respectively. He joined in the University of Tokyo as a research associate fellow, collaborating with the Komatsu Ltd since 2018. His research is focused on high performance gear skiving technology and relevant fields.

Dr. **FANG Zhenglong** received the B.S. and M.S. degrees in mechanical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2009 and 2012, respectively. He received the Ph.D. degree from the University of Tokyo in 2017, and then joined in the University of Tokyo as the research fellow, collaborating with the Komatsu and Toyota motor. He became an assistant professor in 2020, majoring on the advanced manufacturing technology on the high precision transmission unit, including the internal gear, harmonic reducer, and motor rotor/stator. He received research award (2017) and Numata-award (2021) from the Japan Society for Precision Engineering.

Author contributions Dr. REN Zongwei contributed to the investigation, methodology, data curation, formal analysis, software, and original draft. Dr. FANG Zhenglong contributed to conceptualization, methodology, original draft, review & editing, and project administration. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

基于数值仿真的齿轮车齿前角的影响研究

任宗伟,方正隆

（东京大学工学院机械工程系,东京 113-8656,日本）

摘要:齿轮车齿法是一种相比传统插齿法更加高效的内齿轮加工技术。但该方法刀具工件相对运动复杂,导致局部切削特征变化剧烈,进而引起严重的前刀面磨损。因此需要有效模拟方法以计算局部切削特征,阐明刀具参数对切出侧前角动态变化过程。本文研究了齿轮车齿刀具端刃前角和侧前角对局部刮削过程的影响机制,探索利用改变局部有效前角的方法改善刮削过程的可行性,促进了刀具前角对局部刮削过程变化的理解。通过实现局部有效前角和切深向参数空间内切屑拓扑上的映射,研究了端刃前角和侧前角对切出侧局部前角的影响过程,总结出增加端刃前角和侧前角以改善并增强刮削性能的结论。此外,提出基于参数空间的车齿过程研究方法,用以阐明刀具前角对局部刮削特征的影响,可有效促进基于局部有效前角的刀具参数优化,并可以进一步扩展到其他局部刮削特征分析。

关键词:车齿;数值模拟;参数建模;切削特征;刀具尺寸