論 文 の 内 容 の 要 旨

論文題目　　Design of cutter geometries for high-performance gear power skiving
based on modeling of cutting mechanism
（切削機構モデルに基づく高性能ギヤパワースカイビングのための工具形状の設計）

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The high developed transmissions in electrical vehicle requires gears part with high precision, strength, and integration. In current gear cutting method, gear power skiving is featured of accuracy, productivity, university, and integrability, displayed high potential in internal gear processing. It should be notified that the power skiving was patented in 1910s and the application of that exploded until last few years with the development of numerical controlled machine tool and coating technology.

In power skiving, owing to the complex and constantly changing of tool-chip contact area, it is difficult to get the cutting characteristics directly, such as the rake angle, depth of cut, and cutting velocity. Hence, Explanation of uncut chip geometry (UCG) and cutting characteristics can help for understanding the power skiving process. However, there is almost none UCG with volume calculated in kinematics model. Some researcher employed the CAD/CAM engine- or FEM -based software to obtain the solid volume of UCG or deformed cutting chip. However, the long simulation time, specialized software, and complex post-processing have prevented the wide application for various cutting conditions and cutter geometries.

Despite different simulation approaches were developed to evaluate the cutting process, the systematic description, analysis, and optimization on cutting process or cutter parameters are not enough. Therefore, a novel parametric modeling process based on the kinematic of power skiving was established. The trajectory of cutting edge was calculated based on the kinematics. The sweep surface generated by trajectory of cutting edge is reflected onto the workpiece by Z-map method. The tool eccentricity error of cutter is included in the parametric modeling process, as well. Hence, the surface roughness of workpiece

could be evaluated. The established parametric modeling process could calculate the UCG by differentiating the geometries of two adjacent cuts which are projected on the workpiece. By discretizing the cutting edge, cutting characteristics, such as rake angle, depth of cut and cutting velocity are defined based on the oblique cutting model and visualized on UCG. The cutting force model of single tooth is induced based on the cutting characteristics projected on UCG and extended Kienzle cutting force equation. Time dependent stress and temperature distribution combined with contact area on rake face are estimated based on a neural network, which was established based on a various simulation results in advance. Finally, tool wear was predicted by combining the stress and temperature distribution on rake face.

Cutting mechanism is systematically discussed based on the established parametric model and cutting trials results. Firstly, cutting trials with different eccentricity error of cutter were carried out. Surface roughness of processed workpiece were measured and compared with simulation results which were calculated based on the eccentricity error included parametric modeling. Both the experimental and simulation results show that the eccentricity error and feed speed on tooth trace direction of workpiece denotes the main reason for the irregular surface. Influences of cutting characteristics such as instantaneous rake angle and depth of cut on the cutting process were elucidated by projecting these cutting characteristics on UCG. Further, features of cutting force were explained based on UCG, cutting characteristics, and measured cutting force. The cutting force was calculated based on the integration of discrete cutting edge, which was represented by the oblique cutting model. It is found that the extremely high cutting force occurred in the later passes even if with small radial feed. The high cutting force has caused tool chipping wear and significantly reduced the cutting efficiency. However, even the radial feed in pass 4^{th} is small, the contact length of cutting edge on UCG is highest, indicating that the contact length of cutting edge on UCG is one of the main factors that influence the cutting force. The results verified that the V-shaped UCG contributes to the high load on cutter. Therefore, to avoid the high cutting force, it is of great importance to eliminate the V-shaped UCG for reducing the contact length and keeping cutting efficiency. In addition, it is of great importance to reduce the cutting edge chipping wear caused by high cutting force in the later passes. Therefore, finding approaches to reduce the cutting force and cutter wear and meanwhile improve the cutting efficiency is the main objective for the cutter geometries.

A full analysis on the influences of cutter geometries on the cutting process including surface roughness of the processed workpiece, UCG, cutting characteristics, and cutting force were carried out. The results revealed that the tooth number influence the surface roughness of workpiece. The large tooth number of cutter means the lower feed rate of teeth on workpiece, therefore, the surface roughness of workpiece reduced because the feed rate donates one of the main factors on surface roughness. However, with the increasing of tooth number of cutter, the eccentricity error denotes the other main factor of surface roughness, as a result, surface roughness almost keeps unchanged. With respect to the UCG, cutter parameters, e.g., top rake angle, side rake angle, helix angle, tooth number and addendum modification, could influence the UCG morphology from the aspect of guiding line, which is one of the basic factors for sweep surface. If the cutting parameters changes the guiding line, the UCG could change as well. The results show that top rake angle, side rake angle, helix angle, and tooth number, have a slight influence on UCG morphology, while addendum modification of cutter could significantly change the UCG morphology. The top rake angle and side rake angle could only slightly change the speed on cutting edge. Therefore, for different top rake angle and side rake angle, the resultant movement of cutter and workpiece in cutting position is slight changed. The tooth number of cutter could change the speed of cutter and workpiece in same ratio, as a result, the relative speed of cutter and workpiece is enlarged. Finally, the addendum modification could only change the cutting velocity on cutting edge. As a result, there is a remarkable change in the relative speed between cutter and workpiece in cutting position. Hence, UCGs with different addendum modification are greatly changed. As for cutting characteristics, both top rake angle and side rake angle could significantly affect the instantaneous rake angle distribution or limit values while other cutting parameters.

With respect to cutting force, due to the different cutting characteristics in different passes, it is difficult to evaluate the cutting force as a whole. However, from the point of maximum cutting force in each pass, it can be confirmed that the variations caused by different top rake angle or side rake angle are small compared with that caused by helix angle or tooth number. The reason is considered that due to the increasing of helix angle and tooth number, the depth of cut become smaller. Finally, it was found that the cutters with large absolute addendum value could help reduce the cutting force. The reason is considered that the reduction of contact length between cutting edge and workpiece. The discussion on the influence of different cutter parameters provided theory proof for the proposal of new cutter geometries.

From the results of UCG and cutting characteristics, it is clear that both proper cutting characteristics and shorter contact length between cutting edge and workpiece could help for reducing the cutting force. Both the helix angle and tooth number could provide a proper cutting characteristic on cutting process. However, the two parameters are limited by the interference between cutter and workpiece. Therefore, selecting the proper addendum modification amount is the most appropriate means for reducing cutting force. Therefore, larger radial feed could be applied in later passes when cutters with both small (negative) and large (positive) addendum are employed. However, it should be noted that the cutting time of single cutter tooth is important which could influence the cutting force of whole teeth cutter. The design of experiment method was employed to analyze the main effect of cutter parameters including top rake angle, side rake angle, helix angle, tooth number, and addendum modification, on power skiving performance, respectively. The main factor that influences the maximum cutting force, cutting time, and maximum depth of cut was evaluated in each pass, respectively.

The proposed cutter with addendum modification amount of 3 mm, was fabricated experimentally examined to ensure it could be used for machining gear with high efficiency. The performance of cutter was evaluated from the aspect of cutting force and tool wear. The single tooth cutter could reduce the cutting force above 40% in pass 4^{th} in same cutting condition . The radial feed was improved. Except finishing process, 3-pass feed method was employed. The wear result shows that with the proposed cutter geometries, the chipping wear reduced in late passes.

In conclusion, a parametric modeling process for comprehensive understanding of cutting mechanism of gear power skiving was proposed. The mechanism including surface roughness of workpiece, UCG, cutting characteristics, cutting force, and tool wear were studied. The influences on cutter geometries on cutting process were analyzed. The main effect analysis of cutter geometric parameters on cutting performance was carried out. A cutter geometry for better cutting performance was proposed. Both simulation and experimental results show the great potential of proposed cutter in reducing cutting force, tool wear and improving cutting efficiency.