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A Review on Machining Technology and Cutting Edge Design Methods of Spiral Bevel Gears

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ABSTRACT

Spiral bevel gears are critical high-precision transmission components widely used in demanding fields such as automotive and aerospace. Their performance is fundamentally determined by advanced machining technology and the precision design of cutting tools. This paper provides a comprehensive review of the historical evolution, current status, and future trends in spiral bevel gear manufacturing. It systematically outlines the development trajectory of machining technology, from early mechanical machines to modern fully computer numerical control (CNC) systems, exemplified by Gleason's Phoenix series, and highlights China's progress in achieving technological independence. The review then focuses on the design of cutting tool edges, a key factor influencing tooth surface quality. It analyzes research on edge geometry—from traditional straight edges to advanced curved profiles—aimed at optimizing contact patterns and reducing transmission error. The analysis reveals that while significant advancements have been made, mainstream designs often simplify edge geometry. Consequently, the future direction points toward deeper integration of intelligent, closed-loop manufacturing systems and a shift in tool design philosophy: from passive "form-following" to active "form-creating." This entails designing complex edge geometries based on conjugate surface principles and multi-physics simulations, performed in synergy with optimized process parameters and machine tool dynamics. The integration of digital twins, artificial intelligence, and additive-subtractive hybrid manufacturing is identified as the pathway to achieving next-generation gears with superior performance, precision, and reliability.

KEYWORDS

Spiral Bevel Gears; Machining Technology; Cutting Edge Design; Computer Numerical Control Systems.

1. INTRODUCTION

Spiral bevel gears are indispensable core components in mechanical transmission systems involving intersecting or non-parallel shafts[1]. Renowned for their smooth operation, high load capacity, and compact design, they are the backbone of power transmission in critical industries including automotive, aerospace, marine, and heavy machinery. The performance, longevity, and noise-vibration-harshness (NVH) characteristics of these gear sets are predominantly dictated by two interconnected factors: the capability of the machining technology and the precision of the cutting tool design.

The journey of spiral bevel gear manufacturing has been one of continual technological revolution. It began with the foundational theoretical work and the invention of dedicated mechanical machines by companies like Gleason in the early 20th century. A pivotal transition occurred with the introduction of CNC technology, culminating in systems like the Gleason Phoenix series, which replaced complex mechanical kinematics with multi-axis digital control, enabling unprecedented flexibility and accuracy. Parallel to this global evolution, China's manufacturing sector has progressed from reliance on imported technology to the independent development of fully CNC gear milling and grinding machines, marking a significant achievement in high-end equipment autonomy.

Equally crucial is the design of the cutting tool edge. The tool's geometry is not merely a cutter; it is the definitive "parent surface" that generates the gear tooth flank. Its shape directly governs the resulting tooth surface topography, contact pattern, and ultimately, the meshing performance of the gear pair. Extensive research has been dedicated to optimizing tool edges, moving from simple straight-edged cutters to sophisticated designs featuring double circular arcs or other complex curves. These advancements aim to localize contact, minimize transmission error, and improve load distribution.

However, a review of existing literature indicates that many tool designs remain incremental modifications based on traditional principles, often employing simplified edge geometries. There is a growing recognition of the need for a more fundamental, system-level approach. The future lies not in optimizing the tool or the process in isolation, but in their co-evolution within an intelligent digital framework.

The purpose of this review is to synthesize the historical development and current research landscape of spiral bevel gear machining and tool design. It will first chart the technological progression of manufacturing equipment. It will then critically examine the state-of-the-art in cutting tool edge design and its impact on gear quality. Finally, by analyzing existing limitations and emerging trends, this paper aims to outline the future trajectory of the field, focusing on the integration of intelligent manufacturing systems, physics-based active tool design, and the holistic synergy between the tool, the process, and the machine.

2. RESEARCH ON SPIRAL BEVEL GEAR MACHINING TECHNOLOGY

2.1. Establishment of Spiral Cone Gear Machining Theory

The theory of curved-tooth bevel gears and hypoid gears was proposed by distinguished scientists from the American company Gleason (GLEASON), such as E. Wildhaber and M. L. Baxter, among others. The introduction of this theory simplified and clarified the complex machining principles of spiral bevel gears, thereby enabling them to begin seeing widespread application across various industrial fields.

2.1.1. Development of the First Dedicated Machine for Spiral Bevel Gears

In 1913, Gleason successfully developed the world's first dedicated machining for spiral bevel gears featuring an arc-shaped tooth profile. By 1915, it began to be applied in the automotive industry, driving advancements in automobiles and other industrial sectors. This led to the formation of the Gleason tooth system for spiral bevel gear manufacturing, which pioneered and guided the global production of curved-tooth bevel gears and hypoid gears. Subsequently, propelled by the rapid growth of the automotive and other industries, a comprehensive "Gleason tooth system" manufacturing framework gradually took shape, maintaining a long-term leading position worldwide in the field of spiral bevel gear production.

2.1.2. Application of Numerical Control (NC) Technology

In the early 1960s, Gleason introduced the No. 116 machine, representing the peak of traditional mechanical gear-cutting technology. While inheriting the characteristics of conventional mechanical structures, this model pioneered the transition to numerical control (NC) technology, serving as a milestone that bridged the past and the future. China imported a significant number of these machines at the time, using them as key subjects for study. The digestion and absorption of this technology accumulated valuable experience for China’s subsequent independent research and development of

NC curved-tooth bevel gear machines. By the mid-1980s, Oerlikon applied PLC control technology to its S17 and S27 models. These machines adopted a rotary mechanism that expanded the range of cutter tilt angles and also introduced the tilt semi-generating method. The emergence of such machines marked the end of the traditional mechanical machine era, officially ushering spiral bevel gear machining into the NC age and greatly improving milling efficiency.

2.1.3. Full Digitalization of Spiral Bevel Gear Machining

In 1989, Gleason launched the Phoenix I (Phoenix First Generation) NC spiral bevel gear milling and grinding machines—a major milestone in the history of machine tool development. This series utilized a six-axis NC framework, providing precise control over six degrees of freedom for the tool and workpiece through the coordinated movement of three linear axes (X, Y, Z) and three rotary axes (A, B, C). This structure allowed flexible control of complex tool-workpiece relative motions and, in theory, enabled the machining of various intricate tooth surface curves. The revolutionary significance of the Phoenix I lay in its complete abandonment of traditional mechanical components such as the tilt mechanism, cradle, and complex internal transmission linkages, fully realizing NC adjustment of all machining motions and parameters. This fundamental transformation not only significantly simplified the machine's mechanical structure but also improved dynamic stability and rigidity, ultimately leading to a qualitative leap in machining precision, gear product quality, and production efficiency. Its introduction marked the official entry of spiral bevel gear machining technology into the fully numerical control era, representing a profound and far-reaching technological leap in the field. To further enhance NC machining capabilities, Gleason also developed the "Gleason Expert Manufacturing System (GEMS)" specifically for this series, enabling data exchange and information integration between engineering workstations and NC machine tools.

In April 2003, at the Beijing International Machine Tool Exhibition, Gleason unveiled the column-type NC bevel gear milling machine represented by the Phoenix II, as shown in Figure 1-2, signaling a new stage of development in spiral bevel gear machining technology. The standout innovation of this machine was its integrated column structure design: the tool spindle and workpiece spindle were configured on two perpendicular sides of the column, forming a highly rigid spatial layout. Another key improvement was relocating the B-axis (tool tilt adjustment axis), traditionally positioned on the workpiece side, to the tool spindle side, significantly shortening the motion chain travel. These structural designs endowed the machine with advantages such as compact overall layout, convenient operation, strong dynamic rigidity, and efficient chip removal, laying the foundation for stable high-speed cutting processes. Furthermore, the Phoenix II milling machine pioneered dry high-speed cutting, further boosting machining efficiency.In recent years, Gleason and HELLER have engaged

Figure 1. Gleason Phoenix series bevel gear milling machine

in strategic cooperation to jointly introduce a new generation of five-axis bevel gear machining solutions, such as the Gleason Heller CT800 bevel gear machining center. This center is supplemented by HELLER's proprietary uP-Gear machining technology, developed specifically for its five-axis machining centers. This technology utilizes advanced digital computing programs and control methods to efficiently and precisely machine spiral bevel gears of almost all specifications on five-axis machining centers. The integration of these technologies and equipment provides advanced solutions for efficiently and flexibly machining large-sized bevel gears and meeting specific batch production needs.

2.2. Development of China's Spiral Bevel Gear Machining Technology

In the early stage of China's spiral bevel gear machining technology development, specifically before 1972, the domestic demand for bevel gear machining machines was primarily met through imports, mainly from the Soviet Union, with a smaller number from East Germany and Japan. It was during this period that extended epicycloidal tooth system machines, representing Oerlikon tooth technology, were introduced into China. After 1972, with the easing of Sino-US relations and the lifting of the US embargo on related technical equipment to China, a large number of machines based on Gleason tooth technology began to enter the Chinese market. Despite its late start, significant research achievements were made in the field of spiral bevel gears through the persistent efforts of many domestic experts and scholars. Among them, scholars such as Tao Zeng, Changqi Zheng, and Xutang Wu conducted in-depth research on the design and machining theory of spiral bevel gears, gradually developing a theoretical system with its own characteristics based on learning from foreign achievements. Regarding machining equipment, China initially relied mainly on imports and technical imitation. After digesting and absorbing the relevant theories and machining principles, the Tianjin First Machine Tool Works successfully developed the Y2250 and Y2280 mechanical spiral bevel gear milling machines, achieving a breakthrough from scratch in domestic machining equipment and becoming important machinery for processing spiral bevel gears in many domestic industries.

After 1990, with the rise of NC technology, domestic universities and enterprises, through industry-academia-research collaboration, initiated the independent research and development process of NC machine tools. For example, Qinchuan Machine Tool Group and Xi'an Jiaotong University jointly developed the YH2240 CNC spiral bevel gear milling machine. This milling machine was the first in China to introduce the concept of a "bevel gear machining center," equipped with a six-axis simultaneous control CNC system capable of free-form generation machining and processing gear tooth surfaces of different tooth systems. Its tool system featured an integrated rotary magazine structure that could hold three sets of milling cutters simultaneously, enabling continuous roughing and finishing of a workpiece in a single setup, significantly improving machining efficiency and accuracy.

The Gear Research Institute of Central South University developed CNC milling machines such as YK2212 and YK2245, capable of six-axis five-axis simultaneous control, in 1999 and 2001 respectively. In 2002, the institute, in collaboration with Changsha Hongli Precision Machinery Co., Ltd., successfully developed the YK2045 CNC spiral bevel gear grinding machine, marking a significant breakthrough in China's high-end equipment technology in this field. Based on the principle of multi-axis CNC linkage, this machine tool, through the coordinated control of three linear axes and three rotary axes, could precisely set any relative position and motion trajectory between the grinding wheel and the gear workpiece. Building on this, the system enabled direct computer control of "seven axes with five simultaneously moving," allowing it to grind spiral bevel gears produced by different methods such as form cutting, generating, tilt method, modified roll, and double spiral motion methods. The YK2045 grinding machine not only achieved comprehensive digital control of the spiral bevel gear grinding process but could also be further integrated with gear measuring centers and computer systems to establish a complete "machining-measurement-compensation" closed-loop manufacturing system.

In 2005, Tianjin Jingcheng Machine Tool Manufacturing Co., Ltd. successfully developed the YH6012 CNC curved-tooth bevel gear milling machine, achieving the capability to machine large gears with a maximum diameter of 1250mm. This machine adopted a four-axis CNC servo drive system, based on the principle of the roll method, enabling efficient milling of curved-tooth bevel gears, Zerol bevel gears, and hypoid gears. It innovatively applied the then internationally advanced Cartesian-axis structural design to the field of large machine tools, providing a new technical solution for machining larger diameter gear products. Building on this, the company further launched the upgraded model YH6016 CNC milling machine in 2007, expanding the machining diameter to 1600mm.

At the end of 2005, China's first digital closed-loop production line for spiral bevel gears, built by Zhongda Chuanyuan in Hunan, was officially put into large-scale production. The successful operation of this production line changed the previous passive situation of complete reliance on imports for high-end fully CNC spiral bevel gear machine tools and marked a new level of automation in batch production. In 2010, the YK2275 six-axis multifunctional fully CNC bevel gear milling machine, developed by Tianjin First Machine Tool Works, marked a technological breakthrough in the third generation of curved-tooth bevel gear machining equipment. As a multifunctional CNC machine tool, it was capable of machining both arc-tooth and epicycloidal-tooth spiral bevel gears. The machine possessed strong process compatibility, supporting various gear cutting process methods including form cutting, roll methods (including the tilt method, standard roll method, and modified roll method), and the complete process method. Through an integrated human-machine interface and dedicated adjustment calculation software, operators could conveniently input and modify machine and tool parameters. The system precisely controlled the motion trajectories of each axis based on these inputs, ensuring the stability and repeatability of the machining process. This machine could stably produce gear products meeting the Grade 6 accuracy specified in the GB/T 11365-89 standard.

Figure 2. YK2212B CNC curved-tooth bevel gear milling machine

In recent years, Tianjin First Machine Tool Works has successively developed several curved-tooth bevel gear machining machines, including the YKD2250A CNC curved-tooth bevel gear milling machine suitable for batch or mass production of drive pinions for axles in cars, light/medium trucks, and construction machinery, the YK2212B CNC curved-tooth bevel gear milling machine suitable for machining small-sized curved-tooth bevel gears and hypoid gears for the small reducer industry, motorcycles, and bicycles (as shown in Figure 2), and the general-purpose YK2232 CNC curved-tooth bevel gear milling machine. Meanwhile, Zhongda Chuanyuan in Hunan has developed the CY15C spiral bevel gear milling machine (as shown in Figure 3), a fully CNC small-module spiral bevel gear milling machine featuring six-axis six-linkage dry cutting and full functionality, capable of high rigidity, high precision, and high-efficiency machining of various spiral bevel gears and hypoid gears with extended epicycloidal high teeth and circular arc depthwise taper teeth, as well as the YKA2235 spiral bevel gear milling machine featuring six-axis six-linkage and full functionality for both dry and wet cutting. This series of achievements fully demonstrates that China had essentially mastered the R&D and manufacturing capabilities for fully CNC spiral bevel gear machine tools by the early 21st century, achieving independent capability in high-end equipment in this field.

Figure 3. CY15C spiral bevel gear milling machine

3. DESIGN OF CUTTING EDGE FOR SPIRAL BEVEL GEAR MACHINING TOOLS

The cutting edge geometry of spiral bevel gear machining tools is a critical factor influencing the quality of tooth surface machining. Precise design of the cutting edge geometry for spiral bevel gear machining tools can enhance tooth surface contact performance. Many scholars have conducted extensive research on the design of cutting edge shapes for spiral bevel gear machining tools.

Simon[2], aiming to transform the meshing tooth surfaces into line or point contact, proposed using a milling cutter with a double circular arc profile to machine spiral bevel gears. Based on the optimization and correction of the cutter head profile and diameter during pinion finishing, more ideal load distribution and reduced transmission error were achieved for the spiral bevel gear pair. This approach was successfully applied to hypoid gear manufacturing, providing new ideas for spiral bevel gear tool design. Stadtfeld[3] designed a novel tool composed of four profile segments, which achieved different machining functions through segmentation, significantly improving the meshing performance of the gear pair and possessing high engineering practical value. Li et al. [4] proposed a tooth surface design method for face hobbing spiral bevel gears. By combining tool edge optimization and active control of the tool path, they achieved precise control of the contact pattern and lengthwise flank chamfering using a solid milling cutter without shaft tilt, significantly improving tooth surface contact performance

To enhance the transmission performance of spiral bevel gears under heavy load conditions, avoid edge contact on tooth surfaces, and improve their stress distribution, Mu Yanming et al.[5] investigated a new method for generating spiral bevel gears using arc-shaped cutting edge tools. The researchers conducted systematic tooth contact analysis (TCA) and finite element analysis on gear pairs machined with traditional straight-edge tools and the new arc-edge tools respectively, confirming that the arc-edge structure can effectively improve the meshing performance of spiral bevel gears. Chen Yizhong et al.[6], aiming to improve the smoothness of gear pairs during meshing transmission, proposed machining spiral bevel gears using the duplex helical method based on a circular arc tool profile. Finite element analysis verified that this circular arc tool could optimize the location and shape of the contact pattern, reduce the transmission error of the gear pair, and enhance smoothness and service life. This research provided theoretical support and practical verification for the further application of curved-edge tools in spiral bevel gear machining. To improve the tooth surface contact performance of bevel gears machined by face milling, Nie Shaowu et al.[7] systematically investigated the influence of using a circular arc tool profile on the tooth surface shape. They first completed the geometric design of the circular arc profile, and based on this, derived the cutting edge equations of the tool teeth and the corresponding theoretical tooth surface equations of the machined gear. Tooth contact analysis demonstrated that a reasonable selection of the circular arc profile radius could effectively suppress edge contact, reduce sensitivity to errors, improve the inter-dial contact, and enable correction of the contact pattern. Yang Hongbin et al.[8] analyzed the main causes of noise in spiral bevel gear meshing transmission and systematically explored common methods for improving gear strength and reducing gear noise. Based on this, they designed a tool with a pointed tip and root protrusion structure. This tool could significantly suppress impacts generated during gear meshing in and out, effectively reducing vibration and noise.

Furthermore, many scholars have conducted significant research on the edge design of other gear machining tools, providing valuable references for the design of spiral bevel gear machining tools. Wang Peng [9] conducted in-depth research on the design theory and methods of gear skiving tools, proposing a method to construct the cutting edge by selecting a smooth curve on the conjugate surface, achieving the goal of improving the cutting performance of skiving tools. The innovative application of the surface conjugation principle in this study provided new ideas for the edge design of spiral bevel gear machining tools.To overcome the inherent limitations of traditional gear disc milling cutters caused by machining principle errors, namely their poor versatility as they typically can only machine gears with specific modules and numbers of teeth, Li Haogang et al. [10] took large wind power transmission gears as the research object and conducted an in-depth discussion on their machining principle. The study established a mathematical model for the actual profile curve of the gear involute, systematically analyzed the relative motion trajectory of the conjugate rack tip corner, and derived the root fillet transition curve equation. Based on this, by analyzing the spatial relative position of the root transition arc, the design method for the tooth profile curve was reconstructed, and a dedicated cutting edge curve for indexable disc milling cutter inserts was successfully designed. This design eliminates the machining error of traditional methods in principle. To meet the requirements for high-efficiency and high-precision machining of tangent four-arc harmonic gear pairs, Guo Erkuo et al. [11], based on the two-degree-of-freedom line-surface conjugate meshing theory, proposed a design method for a gear skiving tool used to machine this type of harmonic flexspline. By constructing a mathematical model of the corresponding tooth profile and solving for the conjugate tool surface and its normal equations, they obtained the normal edge profile of the skiving tool without theoretical error. Based on this method, a dedicated gear skiving tool with an end-cutting edge was further designed and manufactured, achieving edge profile construction without normal principle error. Finally, simulation and cutting experimental results showed that the tool with the designed edge profile could effectively ensure tooth profile accuracy, verifying the correctness and engineering applicability of this design method. Aiming at the problem that the current modeling method for gear skiving of crossed-axis face gears cannot be directly applied to the machining of helical face gears, Wang Libing [12] studied the gear skiving principle for offset helical face gears, proposed the corresponding gear skiving modeling and tool design optimization method, and designed a petal-shaped cutting edge tool. Simulation verification showed that the overcut and residual amounts in the face gear skiving simulation were significantly reduced after tool optimization, significantly improving machining accuracy and verifying the rationality of the optimized design of the petal-shaped gear skiving tool.

4. FUTURE DEVELOPMENT DIRECTIONS

4.1. Fully Digitalized and Intelligent Closed-Loop

Future machining systems will no longer be isolated machine tools, but rather intelligent closed-loop manufacturing units that integrate intelligent design (CAD), CNC machining (CAM), online/in-process measurement (CMM), and data-driven compensation. Artificial intelligence (AI) and machine learning (ML) algorithms will be deeply applied to optimize process parameters, predict machining errors, and enable adaptive compensation, thereby realizing an autonomous cycle of "machining–measurement–feedback–correction" that continuously enhances precision and consistency.

4.2. Additive-Subtractive Hybrid Manufacturing (ASHM)

For large gears, gears made of specialty materials, or those featuring intricate internal cooling structures, a hybrid approach will be explored. This involves using additive manufacturing (3D printing) for near-net-shape forming, followed by precision milling/grinding to finish the tooth surfaces. This combined process aims to shorten manufacturing lead times, reduce material waste, and enable lightweight design.

4.3. Further Application of Ultra-High-Speed Dry Cutting

With advancements in machine tool rigidity, power, thermal management technologies, and the development of high-performance coated cutting tools, dry high-speed cutting is set to become a more mainstream green manufacturing technology. Research focus will center on thermo-mechanical coupling control during the cutting process, chip morphology optimization, and the enhancement of machine tool dynamic stability.

4.4. From "Form Imitation" to "Form Creation"

Active Conjugate Cutting Edge Design. Cutting tool design will increasingly rely on the fundamental principles of surface conjugation and gear meshing theory. It will directly derive or optimize the cutting edge profiles based on the desired tooth contact performance, such as contact patterns and transmission error curves. The goal is to design higher-order complex curved cutting edges—such as complex arcs, elliptical arcs, or custom curves—that can directly "generate" the ideal tooth flank geometry, rather than simply approximating the profile of traditional cutter heads.

4.5. Design Optimization Driven by Multi-Physics Coupled Simulation

Cutting tool design will deeply integrate multi-physics simulations such as cutting mechanics, thermodynamics, friction and wear, and residual stress analysis. By comprehensively evaluating cutting forces, temperature fields, tool wear, and workpiece surface integrity under different cutting edge profiles in a virtual environment, multi-objective collaborative optimization of cutting performance, machining quality, and tool life can be achieved.

5. CONCLUSION

The authors declare that they have no conflict of interest.

Spiral bevel gear manufacturing stands as a sophisticated discipline at the intersection of precision mechanics, materials science, and digital engineering. This review has traced its evolution from the foundational theories and mechanical mastery of the 20th century to the current era of digital flexibility and intelligent machining. The development trajectory is clear: from dedicated mechanical machines to multi-axis CNC systems, and now towards fully integrated, data-driven smart manufacturing cells. China's journey in this field, evolving from technology import and assimilation to independent innovation and the development of world-class equipment, exemplifies the global pursuit of technological sovereignty in high-end manufacturing.

The parallel evolution of cutting tool edge design reveals a critical shift in philosophy. Research has progressively moved beyond merely replicating traditional tool geometries towards actively designing cutting edges based on conjugate principles and performance objectives. The goal is no longer just to "cut" a gear, but to "create" an optimal tooth surface with predetermined contact characteristics. However, the prevailing practice often still relies on simplified models and isolated optimization.

Therefore, the future of spiral bevel gear technology will be defined by convergence and synthesis. The main conclusions and forward-looking perspectives are:

1. The End of Isolated Optimization: The highest performance gains will come from the co-design and synergistic optimization of the tool, the process, and the machine tool dynamics. Future systems will treat these elements as an inseparable whole.
2. Paradigm Shift in Tool Design: Tool edge design will undergo a fundamental shift from passive "form-following" to active "form-creating." This will be enabled by physics-based models, multi-physics coupling simulations (integrating cutting mechanics, thermodynamics, and structural dynamics), and the application of advanced optimization algorithms to derive complex, high-performance edge geometries.
3. Dominance of the Digital Thread: A complete digital thread—linking design (CAD), manufacturing planning (CAM), virtual simulation (Digital Twin), physical machining (CNC), and in-process metrology—will form the backbone of production. Artificial Intelligence and machine learning will be embedded within this thread for predictive process control, adaptive compensation, and knowledge-based optimization.
4. Process Integration and Expansion: Hybrid additive-subtractive manufacturing will open new possibilities for complex gear geometries and lightweight structures. Ultra-high-speed dry cutting will mature as the default sustainable process, demanding advances in tool materials, coatings, and machine tool stability.

In summary, the next frontier in spiral bevel gear technology is not merely a step forward in precision or speed, but a leap towards intelligent, self-optimizing, and highly integrated manufacturing ecosystems. Success will depend on transcending traditional disciplinary boundaries, fostering deeper collaboration between academia and industry, and relentlessly pursuing the fusion of physical mastery with digital intelligence. The gears of the future will be born not just from metal removal, but from the seamless flow of data, models, and insight across the entire creation cycle.

REFERENCES

[1] ZENG Tao. Design and Manufacturing of Spiral Bevel Gears [M]. Harbin: Harbin Institute of Technology Press, 1989: 91.

[2] Simon V. Head-cutter for optimal tooth modifications in spiral bevel gears [J]. Mechanism and Machine Theory, 2009, 44(7): 1420-1435.

[3] Stadtfeld H J. Guidelines for modern bevel gear grinding [J]. The Gleason Works, 2008.

[4] Lingzhi L, Wenchao G, Huawei Y, et al. A Novel Cutting Method for Face-Hobbed Spiral Bevel Gears Based on Tool Path Modification [J]. Journal of Physics: Conference Series, 2022, 2185(1).

[5] MU Yanming, FANG Zongde, ZHANG Xijin. Tooth surface design of spiral bevel gears based on tool profile modification [J]. Journal of Huazhong University of Science and Technology (Natural Science Edition), 2019, 47(07): 97-101.

[6] CHEN Yizhong, YAN Hongzhi, AI Wuyi, et al. Full tooth surface partition modification of spiral bevel gears machined by circular-arc cutter profile [J]. Manufacturing Automation, 2019, 41(11): 136-142.

[7] NIE Shaowu, DENG Xiaozhong, LI Tianxing, et al. Meshing contact analysis of face hobbing bevel gears based on circular-arc blade [J]. Journal of Aerospace Power, 2012, 27(06): 1424-1431.

[8] YANG Hongbin, ZHANG Guangjie, LIANG Guiming. Modification design and machining of spiral bevel gears [J]. Journal of Mechanical Transmission, 2008, (05): 93-95+121-122.

[9] WANG Peng. Research on the Design Theory and Method of Skiving Cutter Based on Surface Conjugation Principle [D]. Tianjin University, 2018.

[10] LI Haogang, WANG Xiaoming, ZHANG Zechen, et al. Cutting edge curve design of form milling cutter for large wind power transmission gears [J]. Manufacturing Technology & Machine Tool, 2023, (02): 57-65.

[11] GUO Erkuo, XU Jia, HONG Yang, et al. Skiving machining of harmonic flexspline with four tangent arcs and its cutter design method [J]. Journal of Mechanical Transmission, 2024, 48(12): 8-14.

[12] WANG Libing. Optimal Design of Skiving Cutter for Skiving Machining of Helical Face Gears [D]. Xi'an Technological University, 2024.

[13] CHEN Zhixin. Principle of Conjugate Surfaces and Its Application [M]. Beijing: China Science and Technology Press, 2008.

[14] LI Jingcai. Research on Fundamental Application Technology for Digital Manufacturing of Spiral Bevel Gears [D]. Tianjin University, 2008.

[15] YAN Deshuang. Research on Forming Theory and Machining Method of Line Contact Tapered Spiral Bevel Gears [D]. Tianjin University, 2021.

[16] LI Zengbin, GUO Mingqian. Research on active design and machining method for spiral bevel gears [J]. Machinery Design & Manufacture, 2024, (09): 51-57.

[17] ZENG Mao. Rapid Machining Simulation Method and Process Optimization of Spiral Bevel Gears [D]. Chongqing University of Technology, 2024.