Spiral Bevel Gear Manufacturing Technology: A Review

Hoang Thuy Dinh, Van Tuan Pham, and Quoc Hoang Pham

Abstract The research on improving the manufacturing quality of spiral bevel gear transmissions has been widely considered by many researchers worldwide. This study presents a survey of research works published in the past 15 years on the manufacturing technology of spiral bevel gears, including cutting methods, cutting machines, cutting tools, manufacturing error, and measurement. The survey results show that spiral bevel gear manufacturing technology has made many advances in recent years, and the manufacturing quality has been increasingly improved. Many advanced research methods have been applied, such as finite element simulation and loaded and unloaded teeth contact analysis to optimize tooth surfaces. Computer numerical control (CNC) machining machines, coordinate measuring machines, and surface coating cutting tools have improved productivity and machining accuracy. The review results provide a better understanding of the spiral bevel gear manufacturing technology.

Keywords Spiral bevel gear · Manufacturing technology · Tooth contact analysis

1 Introduction

The spiral bevel gears are commonly used to in various mechanical products such as: mining machinery, vehicles, robot, automation, helicopters and aerospace engineering because of their high strength, high contact ratio and smooth driving [1–3].

Due to the complication of tooth surface and cutting kinematic, machining process of spiral bevel gear becomes difficult to understand and analyze. Therefore, the research on manufacturing technology of spiral bevel gears to improve machining quality is always a topic of interest to many scientists.

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B. T. Long et al. (eds.), *Proceedings of the 3rd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2022)*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-57460-3_7

This paper presents an overview of the spiral bevel gear machining methods, machine and cutting tools for processing spiral bevel gear, manufacturing errors and measurement of spiral bevel gear, and research trends in spiral bevel gear.

2 Main Cutting Methods

Spiral bevel gears can be manufactured on CNC universal milling machines [4–6]. However, in industry spiral bevel gears are mainly cut on specialized machining machines because of their high productivity. The main cutting methods on these machines are face milling and face hobbing [1, 7–10].

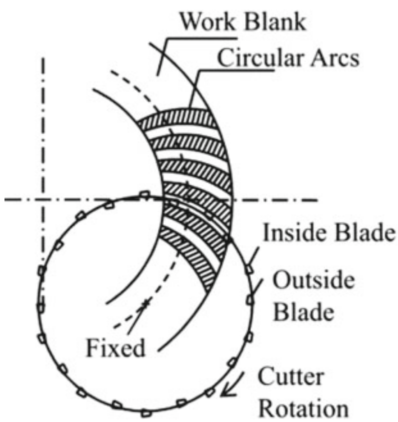
In face milling method, only one slot is machined at a time until the full depth is cut, so it's called the single indexing method. After completing one slot, the workpiece will rotate to the position for machining next slot and the process will be repeated until all tooth spaces are completed. Lengthwise tooth curve of face milled bevel gears is circular. Kinematic of face milling method is shown in Fig. 1.

In face hobbing method, all the tooth spaces are cut at a time, so it's called the continuous indexing method. The cutting system, besides the rotation around its axis, also performs a relative motion with the rotation around axis of the workpiece so that each slot is cut a little until the final requested depth. Face hobbed gears have an extended epicycloid lengthwise tooth curve. Kinematic of face hobbing method is shown in Fig. 2.

The tooth depth and thickness of face milled gears are tapered (the depth and thickness at the toe is usually smaller than at the heel) and slot width may be constant [12] (Fig. 3). Similar to face milled gears, face hobbed gears have tapered tooth thickness but tooth depth is constant and slot width is tapered (Fig. 4).

Regarding the forming method, both generating and non generating (Formate) method can be used for both face milled and face hobbed gears, but the opinion is always cut with the generating method.

Fig. 1 Kinematic of face milling method [11]



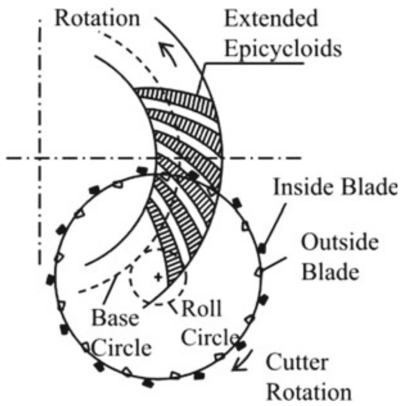


Fig. 2 Kinematic of face hobbing method [11]

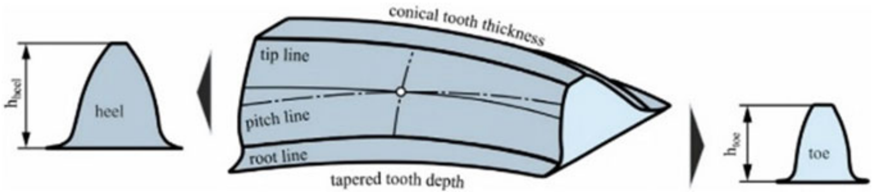


Fig. 3 Tooth geometry of face milled gears [7]

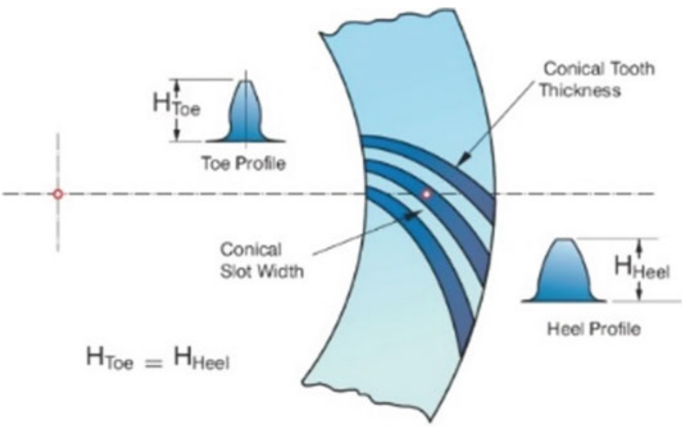


Fig. 4 Tooth geometry of face hobbed gears [13]

3 Cutting Machines

In the early period, the traditional cradle-style machines are used to produce spiral bevel gears. They consisted of many components cutter spindle, tilt drum, swivel drum, eccentric drum, cradle, sliding base, machine root angle, machine center to back, blank offset and work spindle (Fig. 5). The drive trains of these machines is very complex because of using many meshing gear pairs (Fig. 6).

Nowadays, spiral bevel gear cutting machines have been greatly improved from earlier machines. Today's modern machine is numerically controlled by computers (CNC machine) with direct-drive technology and high-speed spindles for both the

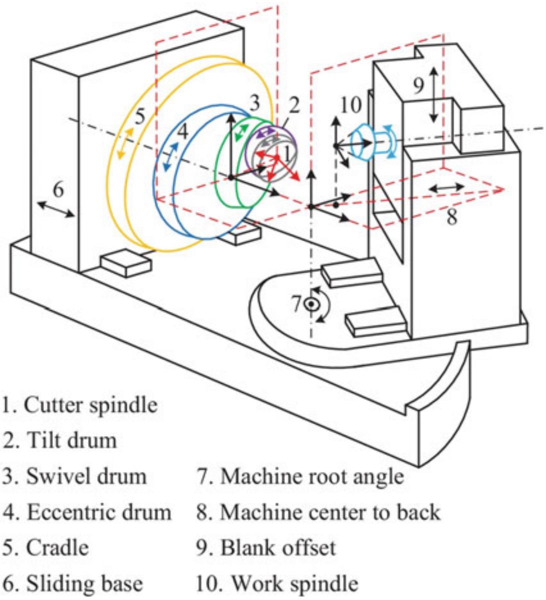


Fig. 5 Traditional cradle-style spiral bevel gear machine

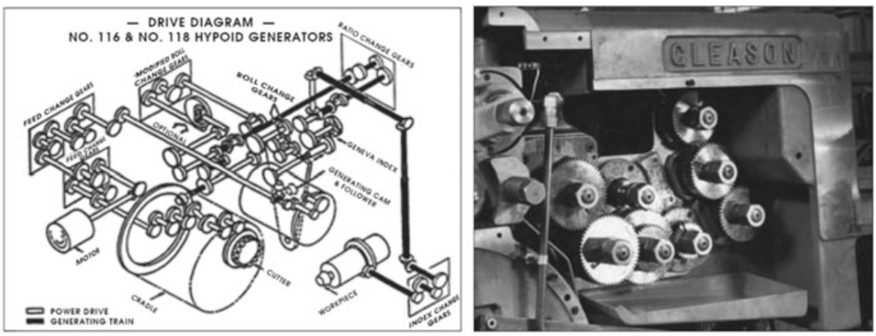


Fig. 6 A drive system of traditional cradle-style machines [12]

work and cutter. The machine itself may not contain any gears. CNC spiral bevel gear cutting machine is composed of six kinematical components. The cradle motion in the traditional cradle-style cutting machines is replaced by a vertical slider (Y-axis) and a horizontal slider (X-axis) in CNC machine (Fig. 7). Figure 8 shows a German spiral bevel gear cutting machine Klingelnberg C27.

The traditional cradle-style cutting machines and CNC spiral bevel gear cutting machines have a similar machining principle. The cutting motions of traditional machines can be converted into the motions of CNC generators by computer control.

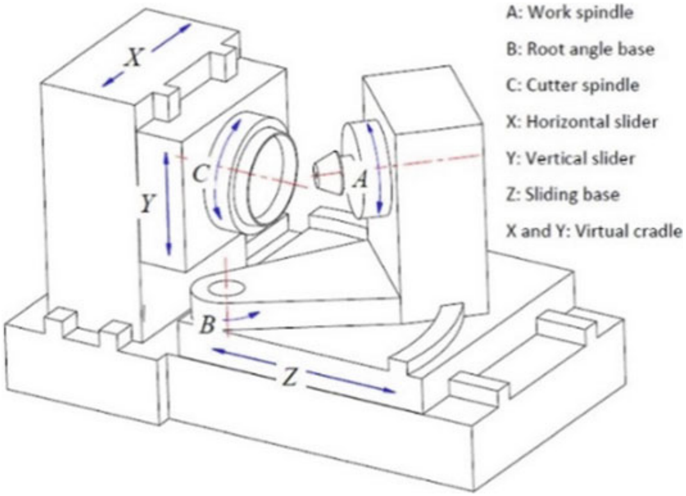


Fig. 7 Six-axis CNC bevel gear cutting machine [14]

Fig. 8 CNC spiral bevel gear cutting machine Klingelnberg C27

In CNC generators, the servo motors directly driven six axes so that can implement prescribed motion functions. In comparison with traditional cradle-style machine, the CNC spiral bevel gear cutting machine has outstanding productivity and accuracy because the machine has better stability and solidity, allowing high speed and precision machining.

4 Cutting Tools

4.1 Cutter Systems

There are different types of cutter system, because each supplier provides its cutter system for different methods of machining gears. In the early days cutters were manufactured in three typical types for machining spiral bevel gears by the face milling method [12]. The first type is integral blade cutter system or solid body cutters, their blades and head are one solid block (Fig. 9). The second type is segmental blade cutter system that has groups of blades fastened to the cutter head by bolts. The last type is inserted blade cutter system, in which individual blades are bolted to slotted heads (Fig. 10).

In the 1970s, a new type of cutter system was invented, that was stick blade cutter system (Fig. 11). In comparison with previous types of cutter system, this type has more blades can be fastened in the cutter head.

In the first three cutter system type, a three-blade configuration was utilized in the blade grouping including an inside, an outer, and a bottom blade. Stick blade cutter systems use only inside blades and outer blades.

Fig. 9 Integral blade cutter system

Fig. 10 Inserted blade cutter system

Fig. 11 Stick blade cutter system

4.2 *Cutting Tool Materials*

From the 1900s–1940s, only one cutting tool material was used that is 18–4–1 high speed steel, which consisted of 18% wolfram, 4% chromium, and 1% vanadium [12]. Today many high-speed steels are used for cutting tool materials as listed in Table 1. These steels are added about 4.5–7.0% molybdenum and 5.0–9.0% cobalt, hardness reaching 64–70 HRC.

Along with developing composite materials, spiral bevel gear cutting tools are also researched and made from composite materials consisting of hard carbide particles bonded together by a cobalt binder. Carbide hardness is more significant than steel (about four times). So the use of composite materials improves cutting speed and does not require the use of coolant to increase productivity and reduce product costs. However, using composite materials as cutting tools has the limitation that carbide particles may shatter the gear surface, increasing the surface roughness.

Nowadays, surface coating technology is increasingly developing, which makes cutting tool manufacturing reach a new step. Cutting tools with coatings are becoming increasingly popular due to their advantages, such as high hardness and good wear

Table 1 Today's high-speed steel cutting tool materials

	C	Cr	W	Mo	V	Co	HRC
CPM M2	1.0	4.2	6.4	5.0	2.0	–	64
CPM M4	1.4	4.3	5.8	4.5	3.6	–	64
CPM REX 45	1.3	4.1	6.3	5.0	3.1	8.3	66
CPM REX 54	1.45	4.3	5.8	4.5	3.6	5.0	65
CPM REX 76	1.5	3.8	10.0	5.3	3.1	9.0	67
CPM REX 86	2.0	4.0	10.0	5.0	5.0	9.0	68
CPM REX 121	3.3	3.8	10.0	5.3	9.0	9.0	70
CPM T15	1.6	4.0	12.3	–	5.0	5.0	66
ASP 2023	1.3	4.2	6.4	5.0	3.1	–	64
ASP 2030	1.3	4.0	5.0	6.5	3.0	8.0	66
ASP 2060	2.3	4.0	6.5	7.0	6.5	9.0	68
M35V (Conventional)	1.2	4.1	6.0	5.0	3.0	5.0	66

resistance, which increases tool life, machining speed, and accuracy. Some of today's coatings and their the properties are listed in Table 2 [12].

5 Manufacturing Error and Measurement

5.1 Manufacturing Error

There are two major classes of the manufacturing errors of a spiral bevel gear, such as dimensional (or macrogeometry) errors and microgeometry errors [15]. The most significant macrogeometry error is the tooth thickness error, which is the leading cause of increase or reduction of the backlash between the meshing gears. Increase of the backlash can cause the noise (on reversal) and reduce effective tooth strength.

Microgeometry errors can be divided into two types: form errors and location errors. Form errors include profile errors and lead errors, meanwhile pitch errors and runout are important regarding location errors (Fig. 12). The quality and functional performance of gears are greatly influenced by the number and magnitude of these errors.

Profile error is one of the main sources of the noise of gear transmission and also increases localized contact stress to accelerated gear wear and fatigue. The main causes of profile errors are geometric deviations in cutting tool and mounting errors.

Lead error can cause transmission problems with non-uniform motion, uneven loading, and localized loadbearing leading that make gear wear go faster. Lead error also affects the gear torque transfer capacity.

Pitch errors and runout are causes of problems of structural integrity. Pitch errors lead to non-uniform motion that causes transmission errors. Runout may affect most

Table 2 Some of today's coatings

	TiN	TiCN	AlNite®	TiAlN-X-CEED	TiAlN- + WC/C	AlCrN	nACo
Hardness	2300	3000	3300	3300	3000	3200	4590
Coefficient of friction	0.4	0.4	0.30–0.35	0.4	0.15–0.20	0.35	0.45
Max. service temp	600 °C	400 °C	900 °C	900 °C	800 °C	1100 °C	1200 °C
Coating color	Gold	Blue–Grey	Violet–Grey	Blue–Grey	Dark Grey	Blue–Grey	Violet–Grey
Coating structure	Mono-layer	Multi-layer	Nano	Mono-layer	Multi-layer	Mono-layer	Nano

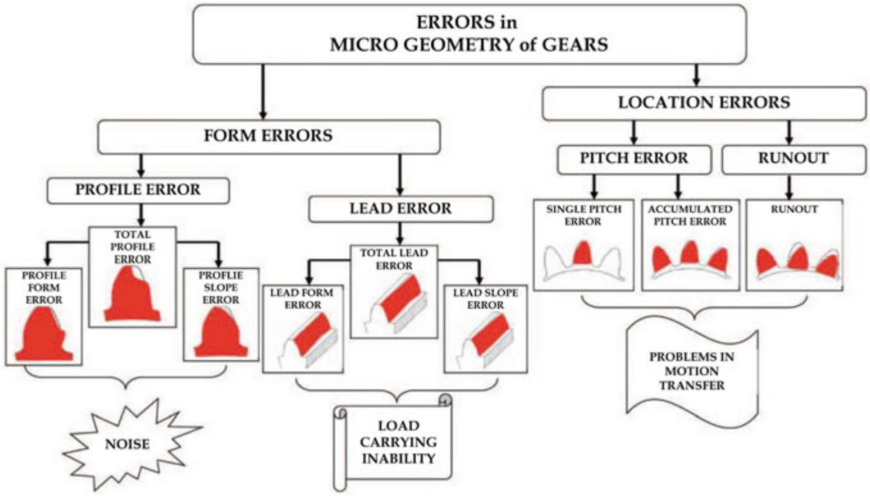


Fig. 12 Microgeometry errors of gears and their effects [15]

other gear quality parameters such as tooth form errors, lead deviation, pitch errors, and noise and vibration. The primary causes of location errors are cutting machine kinematic errors and mounting.

5.2 Measurement

Due to the complex geometrical profile, spiral bevel gears are challenging to measure geometrical parameters by traditional mechanical generative instruments. During the spiral bevel gear manufacturing process, the macrogeometry parameter (chordal tooth thickness) is monitored as process control. For measuring chordal tooth thickness, the most frequently used tool is the gear tooth Vernier caliper (Fig. 13). This method has accuracy limitations due to the double Vernier scale reading interrelationship. The most accurate and advanced method to measure the spiral bevel gear microgeometry error is to use a coordinate measuring machine (CMM) (Fig. 14).

The CMM can measure all microgeometry parameters (profile, lead, pitch, and runout) with high accuracy and reliability, thereby determining the manufacturing errors and the accuracy level of the manufactured gears. A typical result of pitch and runout measurement by CMM is shown in Fig. 15, and the profile error is shown in Fig. 16. The inspection results are used to evaluate the quality of the manufactured gear and adjust the manufacturing process parameters to improve machining accuracy.

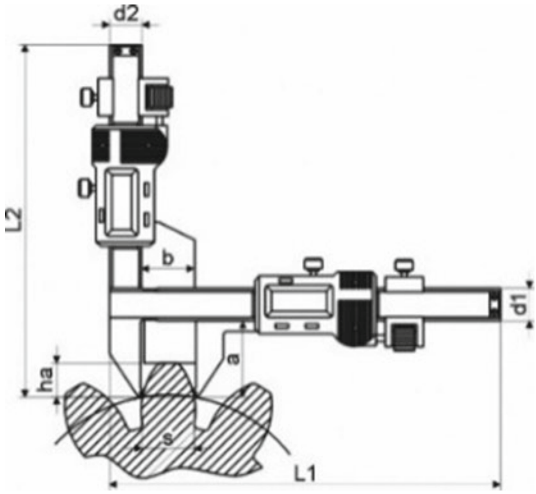


Fig. 13 Gear tooth vernier caliper

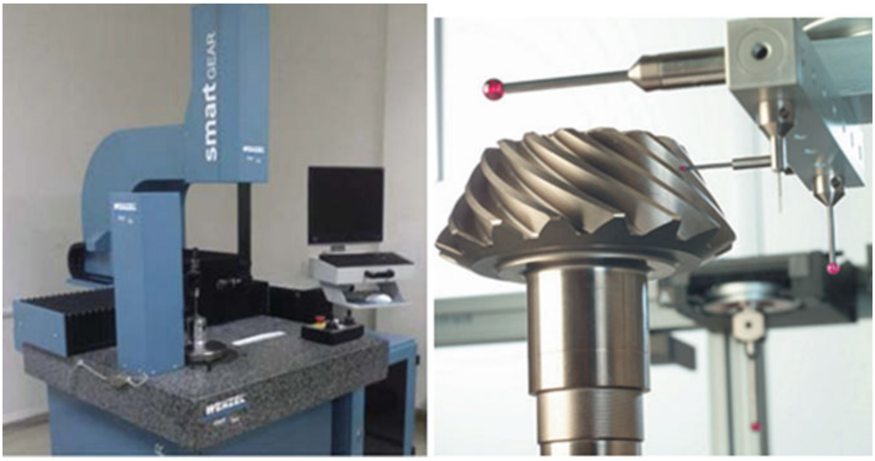


Fig. 14 Coordinate measuring machine

6 Advanced Research Trends

Nowadays, research trends that are concerned too many researchers are optimizing tooth contact area and reducing transmission errors. The transmission errors of gear pair and contact pattern can be determined using a meshing simulation. The purpose of optimizing tooth contact is to adjust the meshing area of the gears to increase load capacity, reduce tooth edge wear and thereby increase gear life. The transmission error is an important cause of the gear noise and vibration. Tooth contact analysis (TCA) technology is an effective tool for gear meshing performance assessment

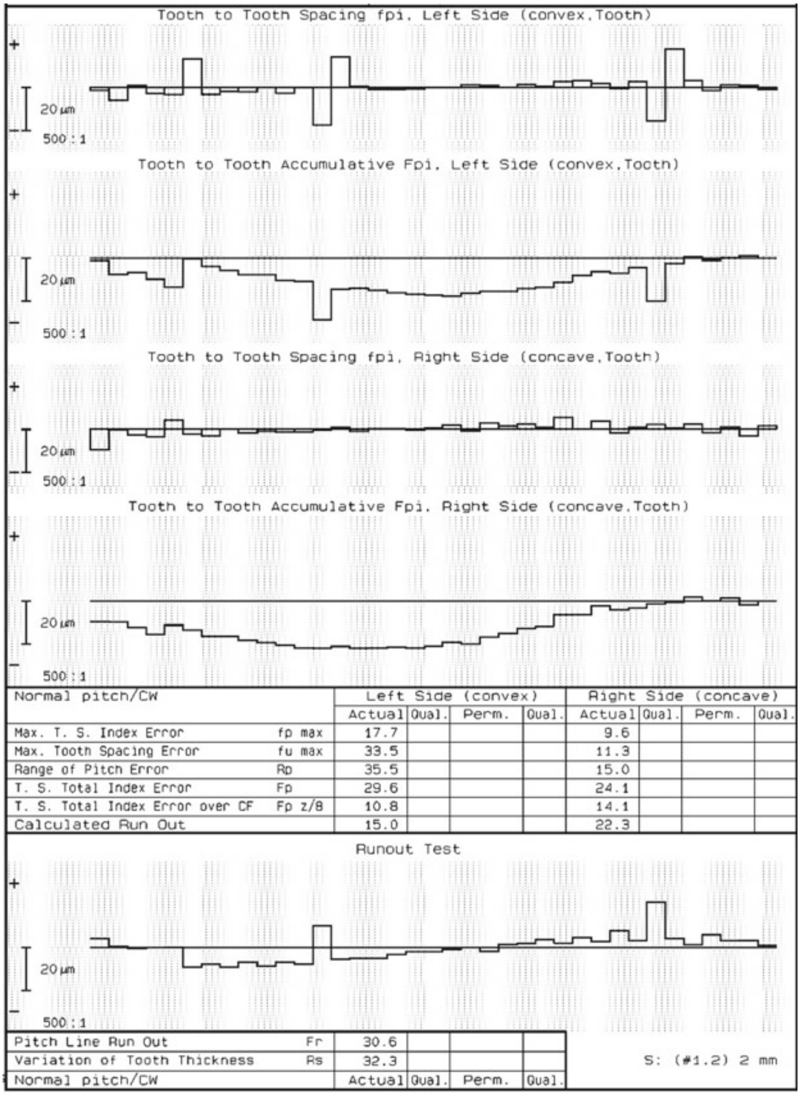
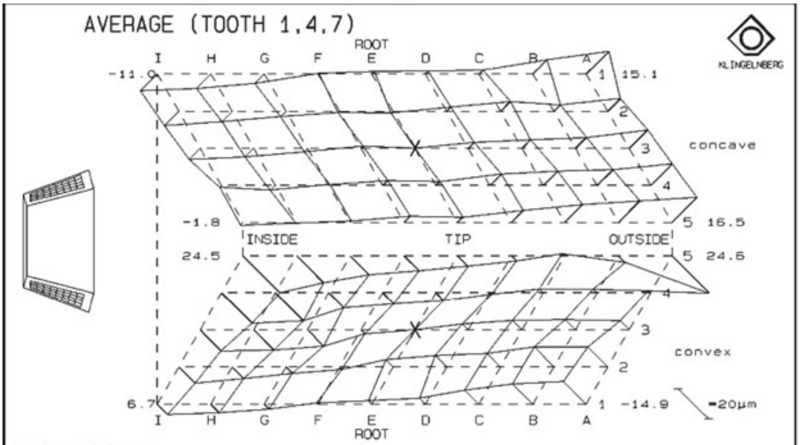


Fig. 15 The typical result of pitch and runout measurement

to improve gear quality in terms of vibration, strength, and mechanical efficiency. Today, scholars worldwide are interested in loaded tooth contact analysis (LTCA)—the new optimization method for improving the power and contact performance of bevel gears.

Artoni et al. [16, 17] developed an approach to automatically optimizing the spiral bevel gear loaded tooth contact pattern. Then, a methodology was presented to



S: (#2.1) 3 mm

Parameter	Nominal	Actual	Dev.	l.Tol.	u.Tol.	Unit
Sum of Squared		6459.3				μm^2
norm.chor.thickness	7.394	7.395	0.001			mm
(E3; R=29.587; Z=22.293)						mm
Mounting distance	115.8000	115.8000	0.0000			mm
Tooth height	8.968	9.017	0.049			mm
tip cone angle	20° 53´10'	20° 59´46	0° 06´36″			DEGREE
root cone angle	14° 58´56'	14° 59´12	0° 00´17″			DEGREE

	concave			convex			
Parameter	Dev.	l.Tol.	u.Tol.	Dev.	l.Tol.	u.Tol.	Unit
Pressure Angle	-0° 03´55			-0° 08´15			DEGREE
Spiral Angle	0° 01´35'			0° 01´48″			DEGREE

ROOT

	I	H	G	F	E	D	C	B	A
concave 1	-11.0	-9.6	-6.1	0.7	1.6	1.9	2.6	9.6	15.1
concave 2	-9.5	-6.9	-3.6	-1.1	-1.3	2.7	6.4	4.1	8.3
concave 3	-7.3	-5.7	-2.1	1.4	0.0	4.0	5.8	7.2	12.1
concave 4	-1.2	-3.3	0.8	3.3	2.5	7.5	9.5	10.4	14.3
concave 5	-1.8	-0.6	0.9	4.1	3.6	8.1	11.6	14.2	16.5
INSIDE — TIP — OUTSIDE									
convex 5	24.5	17.8	12.5	9.9	7.0	3.5	-1.3	4.5	24.6
convex 4	20.2	18.6	9.8	7.3	5.0	1.1	-2.7	-2.4	-1.6
convex 3	13.9	13.2	10.7	2.5	0.0	-4.0	-6.1	-6.7	-6.0
convex 2	10.6	7.6	4.2	1.6	-4.9	-7.5	-8.7	-13.2	-13.1
convex 1	5.7	5.8	3.1	-0.8	-2.2	-3.9	-9.2	-13.2	-14.9

I H G F E D C B A
ROOT
Unit: [μm]

Fig. 16 Typical result of profile error

minimize the hypoid gear loaded transmission error (LTE) by systematically determination of the optimal ease-off topography. Astoul et al. [18] developed a methodology of automatically designing process of the spiral bevel gear flanks to reduce the quasi-static transmission error. Simon [19–21] studied on some of causes of loaded transmission and tooth contact pressure errors included machine settings and misalignments to propose a method to improve gear meshing performance of hypoid gears by reducing the loaded transmission error and the maximum tooth contact pressure. Zhuo et al. [22] analyzed the spiral bevel gear contact characteristics under quasi-static conditions and presented a method to globally optimize the tooth contact pattern and transmission error.

7 Conclusions

Spiral bevel gear manufacturing technology has been developed over the years with advances in cutting machine, cutting tools, measuring machine and software. Today, modern cutting machines without coolant using coated carbide tools allow the spiral bevel gear machining with high precision and productivity.

The measurement method by CMM also decides the gear manufacturing errors become more accessible and accurate. Measurement results evaluate the accuracy level of manufactured gears and adjust the manufacturing process parameters to improve machining accuracy.

The development of simulation tools has provided more modern research methods such as loaded and unloaded tooth analysis. This helps to understand the gearing process better, thereby providing design adjustment solutions to improve the transmission quality of the gears.

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