PRACTICAL EXPERIENCE IN DESIGN AND MANUFACTURING OF SPIRAL BEVEL GEARS ON UNIVERSAL CNC MILLING MACHINES

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Abstract: *Manufacturing of spiral bevel has been traditionally done on special machines commonly known as Gleason, Oerlikon, or Klingelnerg. Disadvantages of the traditional method are high cost and high dependence on existing monopoly of Gleason and Klingelnberg. Many gear manufacturers around the world start using universal CNC milling machines for cutting of spiral bevel gears with very good results in cost reduction and superior quality compare to gears made on Gleason/Klingelnberg machinery. This article presents author'spersonal experience in CNC gear machining that started in 1986 at Mil Helicopter in Moscow, USSR and continued its development in the USA today. Manufacturing of gears on universal CNC milling machines has been recognised around the world as a better way to make gears, particularly gears that require expensive machinery like spiral bevel, hypoid or globoid. Using CNC machining method can significantly benefit countries that start new gear production factories from scratch like Russia, Ukraine, India, Brazil, China, Iran, Republic of South Africa, or, indeed new born Republics of Donetzk and Lugansk that may need to rebuild industry from ground level. CNC method does not require special gear manufacturing equipment, while it provides gears similar or better compare to traditionally used Gleason or Klingelnberg methods. Since 1998 the author hashelped to set up CNC gear production for 30 companies in 20 countries including USA, Germany, India, China, Brazil, Pakistan, Iran, South Korea, Turkey, Poland, Czechoslovakia, Belgium, Italy, UK, Republic of South Africa, Africa, Sweden, Finland, Australia, New Zealand, and other. The intension of this article is to inspire production of higher quality gears on universal CNC machines as a better alternative to traditional domination of Gleason and Klingelnberg.*
Key words:*Gleason, Klingelnberg, spiral bevel, hypoid, tooth contact, CNC.*

The idea of cutting gearson universal CNC milling machines existed beforethe author started to work on it in 1986 at Mil Helicopter in Moscow, USSR by developing Direct Digital Simulation(DDS) 3 dimensional tooth modelling method [1], [2], [3], [4]. The first FORTRAN version was used for Tooth Contact Analyses (TCA) in production of spiral bevel gears for main and tail gearboxes of Mi-24, -26,-32,-28 helicopters. Because of USA sanctions due to International mission in Afghanistan Gleason stopped supporting critical software that was required for manufacturing of helicopter transmission gears. Author has developed a new computer based method (DDS) for calculation of gear machine summary and simulation of the tooth contact pattern in order to substitute Gleason software. Soviet originated method has been productively applied for variety of gears including spiral bevel, hypoid, globoid, worm face, worm, helical, variable ratio rack, and other gears [5]. In 2006-2009 world mining and oil drilling industry experienced shortage in supply of spiral bevel gears over 1500mm in diameter. Large spiral bevel gears were needed for oil drilling rotary tables and for rock crashers. There only two suppliers, Klingelnberg (Germany) with its US strategic partner Overton and Brad Foote (US), could not satisfy demand for large gears. In result, cutting gears on CNC machines started to become very popular. Manufacturers of universal CNC machines started to advertise spiral bevel gear cutting on commonly used 5-axis milling machines. CNC gear cutting has become very popular in very short period of time because of better quality and lower cost of production gears. Klingelnberg and Gleason started to use CNC gear cutting process in addition to their traditional method. In 2008-2009 the author has assisted to Overton Gear, the strategic partner of Klingelnberg, to develop rough cutting of spiral bevel gears before case hardening with following hard cut on

Klingelnberg machines. In the same time, the author assisted DeckelMahoGidemeister, in developing of 3d modelling software for spiral bevel gears. In 2009-2010 the author has provided 3d gear tooth modelling software for other key companies like Brad Foote, NOV, Metso, Mazak, Breton, and otherscontributing to the industry shift from Gleason/Klingelnberg method to CNC method. In 2009, the author actively has participated in production of 1700mm diameter case hardened spiral bevel gears for MP1000 crashers from Metso Minerals using 3-axis CNC milling machine resulted in adopting of the CNC method for manufacturing of bevel gears in value of over $50 million per year. Author's assistance to numerous companies around the world doubled in consecutive years of 2013 and 2014 that demonstrates advantages of the CNC method versus traditional Gleason or Klingelnberg method. This article providesinitial guidelines to start a new production of bevel and other complex gears with minimum cost and superior quality compare to traditionally used Gleason or Klingelnberg method.

Table 1 shows comparison of the traditional bevel gear cutting versus CNC gear cutting in cost for gear size up to 1500 mm in diameter.

Table 1 - Cost comparison of Gleason or Klingelnberg methodversus CNC method

	Gleason or Klingelnberg method	CNC method
Tooth cutting machine	$2,000,000.00US	$600,000.00US
Tooth grinding machine	$2,000,000.00US	0 (not needed)
Cutter assembly machine	$400,000.00	0 (not needed)
Cutter sharpening machine	$800,000.00	0 (not needed)
Gear cutter cost	$40,000.00	$300.00
Quench press	$2,000,000.00	0 (not needed)
CMM inspection machine	$400,000.00	$400,000.00
Inspection for burning after grinding	$1,000.00 per set average	0 (not needed)
Extra gear set for tooth contact development	$20,000.00 per drawing	0 (not needed)
Experienced gear engineer	$200,000.00 per year	0 (not needed)
Experienced machine operator	$100,000.00 per year	$70,000.00 per year
Gear software	$100,000.00 per license	$500.00 per license

Spiral bevel gear cutting machines are about 3 times more expensive compare to the same size capacity 5-axis universal milling machines. Many machining shops do not need to buy CNC machines because they already have them. In author's experience, machining shop purchased a large 3-axis CNC machine for cutting large diameter gears and smaller 5-axis machine pinions. Figure 1.

Fig. 1. 3-axis universal CNC milling machine with 1800 x 2500 mm table for $500,000.00US

Note, that large and flat gears can be cut using only 3 axis. Often, when customers need gears, they buy 3d gear model and just look around for a CNC milling machine for tooth cutting based on 3d model. Many customers need replacement gears and it is less expensive to order CNC gear milling based on 3d model versus ordering traditional gears tooth generating.

Tooth grinding or hard cutting is used traditionally for improving of tooth surface on case hardened gears. Grinding and hard cutting are expensive. It is also very critical to assure correct and uniform case depth.

Deformations of gears during quenching result in variations of the case depth from tooth to tooth. CNC process allows finish cut of case hardened tooth with special cutters without risk of burning. Author used 12mm diameter ball-end carbide mills ($30.00 each) for finish cut of 1700mm diameter case hardened gear. Total of 10 mills have been used without sharpening. CNC machine automatically takes a new sharp cutter in order to produce the highest accuracy. Figure 2.

Fig. 2. Case hardened Metso MP 1000 gear finished on 3-axis universal CNC milling machine using ten new 12mm ball-end milling cutters ($30.00 each). Dimensions on the picture are in inches

Unlike Gleason or Klingelnberg CNC method does not need cutter assembly and cutter sharpening machines. CNC method needs low cost mill cutters that are commonly used in machining.

It is common to use quench press on case hardened gears if traditionally cut by Gleason or Klingelnberg method. The author made case hardened 1700 mm diameter bevel gears without quench press with better consistency of the case depth. The gear was quenched free hanged resulted in some deformations. If used as is the quenching deformations would result in increase of accumulated transmission error, which is not very critical compare to tooth-to-tooth spacing error. If the gear tooth was finish ground of hard cut by traditional Gleason or Klingelnberg method the variation of the case depth would be unacceptable. CNC method allowed repositioning the finished tooth surfaces on the 3 model of the gear in order to accommodate the real deformations on the gear. In result, the variation of the case depth was within requirement at a minor cost of increase of accumulated transmission error. Because CNC method is based in 3d model it is more flexible in manufacturing compare to the traditional method. The traditional method does not allow smooth adjustment of the accumulated pitch error in order to provide compensation for heat treatment deformations.

3-axis Coordinate Measuring Machine (CMM) is often used today for inspection of gears. Because CNC method uses 3d CAD model for gear tooth machining it makes it easy to inspect the finished tooth on a CMM against its digital 3d CAD master. Tooth contact inspection is normally not needed for CNC method because the tooth contact is verified on the 3d models. [6].

Gear software is the key for correct manufacturing of spiral bevel gears. Gleason and Klingelnberg bevel software is known to be very expensive. It is known to keep customers dependent on Gleason and Klingelnbergsoftware. CNC method does not need special software. CNC method is based on accurate 3d models of the gears. The 3d models are used for programming of the CNC machines. Commonly used CAD/CAM programs are used for CNC programming. The most popular programs are SolidWorks and MasterCAM.

Finally, the big advantage of CNC method is a possibility to make gear design that was impossible with use of Gleason/Klingelnberg methods of cutting. For example, it is possible to increase bending strength of gear tooth by design option shown on Figure 3.

Fig. 3. Increase of the bending strength of the pinion with design improvement on the tooth heel is possible only if CNC tooth cutting is used

Other design advantages for CNC machining are: increased root fillet radius for reduction of root stress, better optimisation of the tooth contact pattern, shaft outside diameter can be as large as gear tooth root because no need for space for gear cutter.

CNC machining of spiral bevel gears has become popular due to significant cost reduction and improvement of quality. Unless, Gleason or Klingelnberg machines are already installed in the factory it is a significant advantage to start new gear production based on CNC method. CNC gear manufacturing method can significantly benefit future economic development by providing a better way to make gears and become independent from existing gear machine monopolies.

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