Fundamentals of Bevel Gear Hard Cutting

Yogi Sharma,
Philadelphia Gear Corporation
King of Prussia, PA

Introduction

Some years back, most spiral bevel gear sets were produced as cut, case hardened, and lapped. The case hardening process most frequently used was and is case carburizing. Many large gears were flame hardened, nitrided, or through hardened (hardness around 300 BHN) using medium carbon alloy steels, such as 4140, to avoid higher distortions related to the carburizing and hardening process.

The use of a quench press can control, but not eliminate distortions. A lapping operation cannot remove runout, pitch error, profile error, and other errors caused by heat treatment distortions. It can only improve active tooth profile finish and tooth contact location, provided that gears did not have excessive errors during soft cutting or high distortions in heat treatment. As a matter of fact, overlapping sometimes does more harm than good on a bevel set.

Bevel tooth grinding was very limited due to cost and size.

Advancement in bevel generators, carbide technology, and many other factors allowed introduction of hard cutting in bevel gears. Initially, the process was limited to special requirements because of low carbide tool life, the need for frequent sharpening, and limited experience. But the picture changed dramatically after some time. The experience gained and the development of the CBN (Cubic Boron Nitride) tool made bevel gear hard cutting very effective from cost and quality viewpoints.

As with any process, hard cutting has its limitations and problems. A properly controlled process, starting from the design concept, good bevel generators, hard cutting tools, including sharpening fixtures, special machines, and trained work force, are a must for successful bevel hard cutting.

This article describes the process and steps required for spiral bevel hard cutting on small batches or in a jobbing atmosphere.

Process Description

Bevel hard cutting can be defined as an operation in which gear teeth flanks are finished by removing the stock allowance left during the soft or rough teeth cutting. The process is similar to gear grinding, with almost all the operations remaining the same, with the exception of tooth grinding, which is replaced by hard cutting.

A simplified manufacturing process sheet for a hard cut bevel gear will contain the following:

- Complete machining of gear blanks for teeth cutting – including various operations, such as turning, milling, drilling and tapping, etc.
- Bevel teeth cutting – consisting of teeth cutting, testing, and any tooth contact development with master or mate, teeth deburring, etc.
- Heat treatment – mostly case carburizing and hardening (nitriding, flame hardening, and induction hardening are rarely used for hard cut bevel gears).
- Finish machining – all machining operations required before teeth hard cutting, such as turning O.D./I.D. grinding, special machining, etc.
- Hard cutting – bevel gear arrives at hard cutting with most or all operations done. It is important that the mating part or master is available for testing purposes. Normally, the gear (member with higher number of

teeth) is finished first and pinion teeth are modified to get correct tooth contact along profile and length of tooth. The modification for length of contact is normally made by change of radius of curvature of the cutting blades. The location of tooth contact along the length is usually controlled by machine settings. The profile correction or modification can be made by different means depending on the type of machine or system used to cut bevel gears, size of gears, and pitch. On fine pitch gears, high pitch line bearing can be obtained by using cutter blades with modified profiles. On coarse pitch gears, profile modification can be made using taper shims. Once the tooth contact requirements are met, the gear teeth are finally checked for spacing and mounted on a gear checker.

- Final inspection – includes dimensional checks, magnaflux, and any other special requirements.

Advantages of Hard Cutting

• Higher power transmission by spiral bevel gears, as both members are case carburized and hardened and finished by hard cutting.

• Higher and predictable quality levels in gear teeth.

• A surface finish of 16 RMS or better.

• Lower noise level, lower internal dynamic forces due to higher geometric accuracy, and better load distribution. A hard cut bevel set significantly reduces the gear box vibration problem caused by higher internal dynamic forces due to poor quality gear teeth, which can cause premature gear box failure.

On the other hand the gear grinding operation is always very sensitive to many factors, such as rate of material removal, grinding wheel, coolant, etc. Any compromise or loose control can cause surface tempering or cracks or both. Surface tempering or cracks are practically unknown problems in hard cutting.

• Hard cutting is performed on the same type of machines as soft-cutting, making the process much more economical. Of course, special tooling is required.

• The same person or group of persons are involved in soft and hard cutting. It has been found that control in roughing operation (soft cutting in bevel gears) is quite important for a successful finishing operation. Proper stock allowance, tooth depth, tooth contact, etc. are necessary for bevel hard cutting. Too much stock allowance can cause loss of case depth and longer cutting times, while too little stock allowance also can cause a variety of problems. Hard cutting time cycles can be reduced by making some adjustments at soft cutting for heat treatment distortions, and it can be done very simply, as both operations are performed by the same person or group of persons.

• Consistency in bevel hard cutting can eliminate the need for matched bevel sets by careful planning. Some of the requirements for elimination of matched sets are as follows:

– Manufacturing and storing of case hardened and hard cut master gear and pinion for checking the gears and pinions in all future setups.

– Optimization of design and cutting data so that it does not have to change for the period unmatched sets are required.

– Tighter control of critical dimensions on gear/pinion blanks. Hard cut unmatched sets are not only useful in assemblies, but they can eliminate many production problems, as each member can be processed independent of others. The unmatched set approach must be used very selectively, as it needs careful planning, customized fixtures, optimized design, cutting summaries, and long term commitment. The unmatched set approach combined with standardized bevel sets can cut down delivery times and cost very effectively in spiral bevel gear boxes.

Preparation

Following are some items which should be considered in detail for successful and economical bevel hard cutting.

Practical Tooth Design. A balanced tooth geometry is a must for a good hard cut set. All new tooth geometry must be reviewed carefully from a manufacturing point of view. In a jobbing or low batch environment, the new tooth geometry should try to use existing tools, as new tool requirements can cause cost and delivery problems. Even in high batch production where tools can be designed around gears, poor tooth geometry can cause multiple problems, such as low tool life, smaller fillet radius, etc.

Gear Blank Design. Fig. 1 to Fig. 4 show a bored pinion, a stem spiral bevel pinion, a solid gear, and a ring type gear. As shown in Fig. 2, the bevel pinion can be indicated in both planes by means of an extra extension in front of the teeth. Both gears show proof bands for indicating the gear blank at hard cutting. Special attention must be paid in blank design so that revalidated proof surfaces at final machining can be used for indication purposes at hard cutting. In high batch production, blanks, truing, and use of proof surfaces are not required because of special customized fixtures. Still, it is good practice to create proof bands at final machining for inspection or assembly purposes. In the

AUTHOR:

YOGI SHARMA *is employed in gear manufacturing and design at Philadelphia Gear Corp. He holds an M.S. degree in mechanical engineering from Villanova University and one in industrial engineering from Penn State. Mr. Sharma is a licensed mechanical engineer in the state of Pennsylvania and a senior member of SME.*

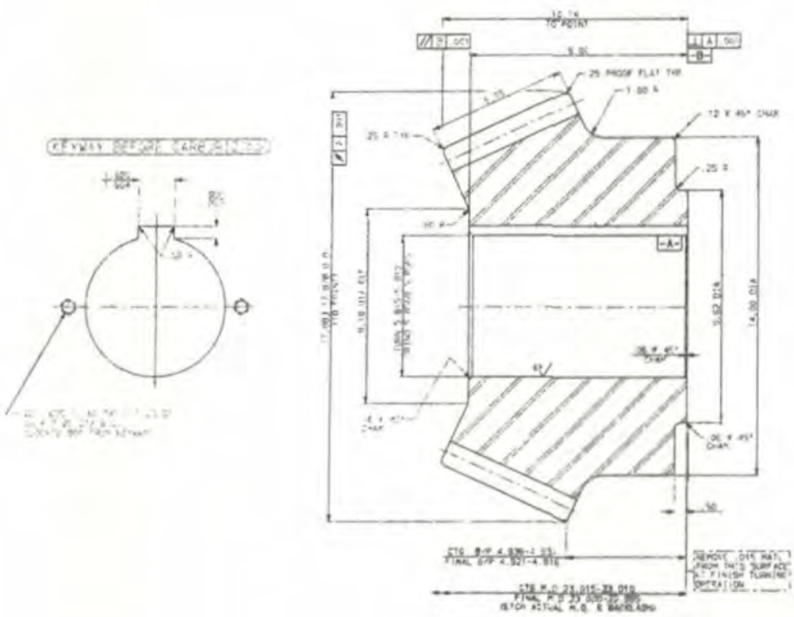

KEYWAY BEFORE CARBURIZING

Fig. 1

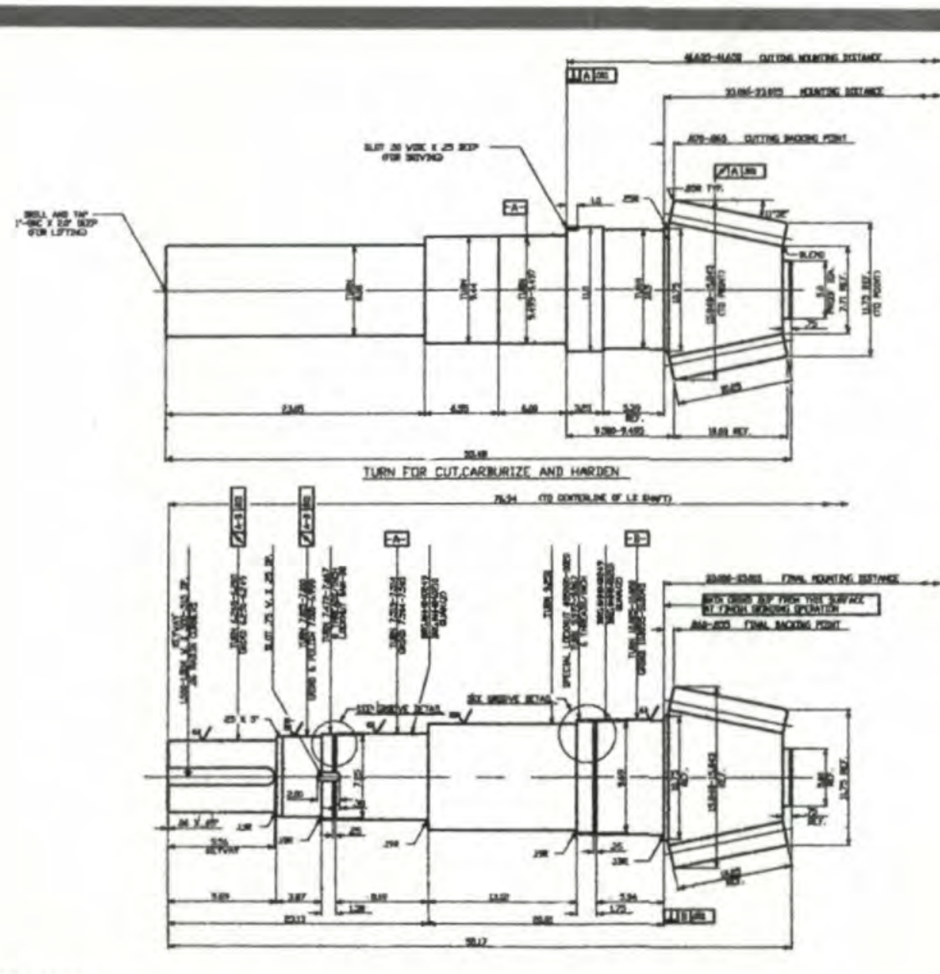

TURN FOR CUT,CARBURIZE AND HARDEN

Fig. 2

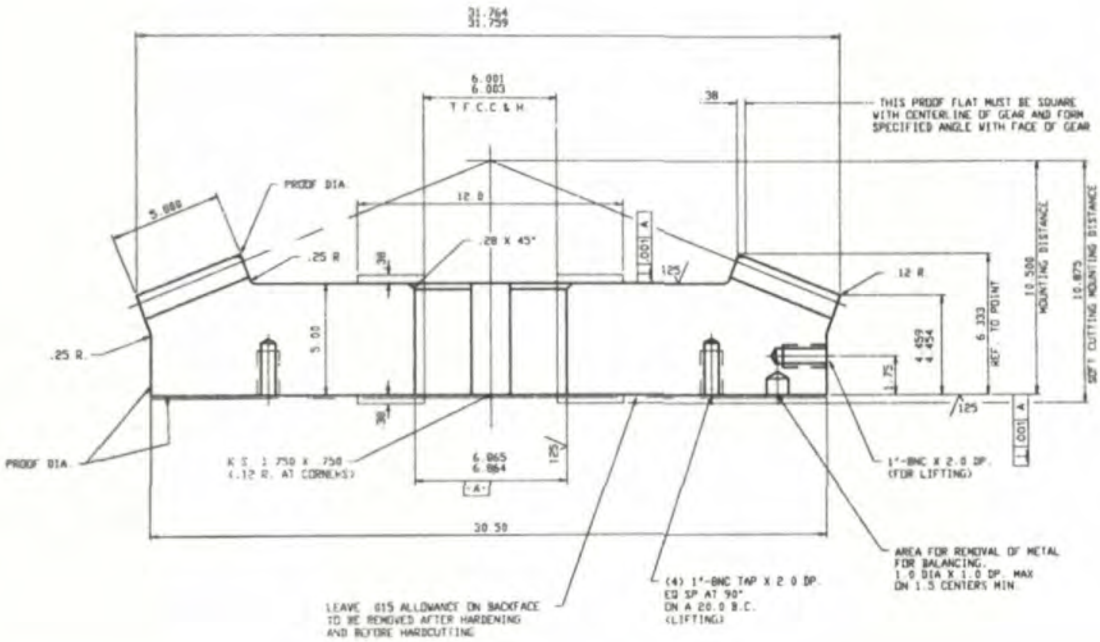

31.764
31.759
6.001
6.003
T.F.C.C.& H.
.38
THIS PROOF FLAT MUST BE SQUARE
WITH CENTERLINE OF GEAR AND FORM
SPECIFIED ANGLE WITH FACE OF GEAR
PROOF DIA.
5.080
12.0
.28 X 45°
.25 R
.001 A
125
.12 R.
10.500
MOUNTING DISTANCE
10.875
SOFT CUTTING MOUNTING DISTANCE
6.333
REF. TO POINT
4.459
4.454
.25 R.
5.00
1.75
125
.001 A
PROOF DIA.
K.S. 1.750 X .750
(.12 R. AT CORNERS)
6.865
6.864
-A-
1"-8NC X 2.0 DP.
(FOR LIFTING)
30.50
AREA FOR REMOVAL OF METAL
FOR BALANCING.
1.0 DIA X 1.0 DP. MAX
ON 1.5 CENTERS MIN.
(4) 1"-8NC TAP X 2.0 DP.
EQ SP AT 90°
ON A 20.0 B.C.
(LIFTING)
LEAVE .015 ALLOWANCE ON BACKFACE
TO BE REMOVED AFTER HARDENING
AND BEFORE HARDCUTTING

Fig. 3

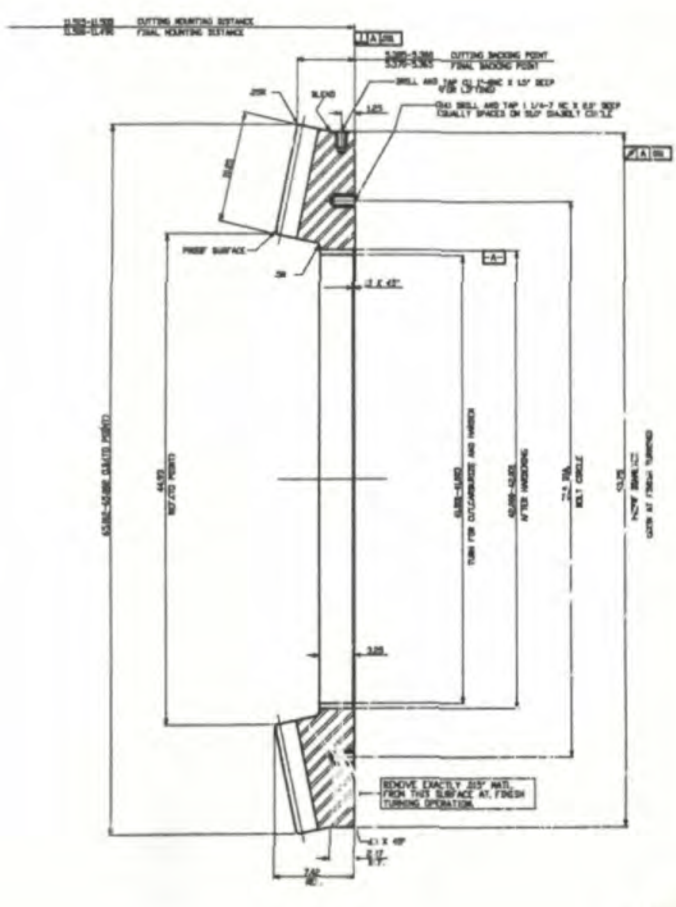

CUTTING MOUNTING DISTANCE
FINAL MOUNTING DISTANCE
CUTTING BACKING POINT
FINAL BACKING POINT
PROOF SURFACE
-A-
REMOVE EXACTLY .015" MAX.
FROM THIS SURFACE AT FINISH
TURNING OPERATION.

Fig. 4

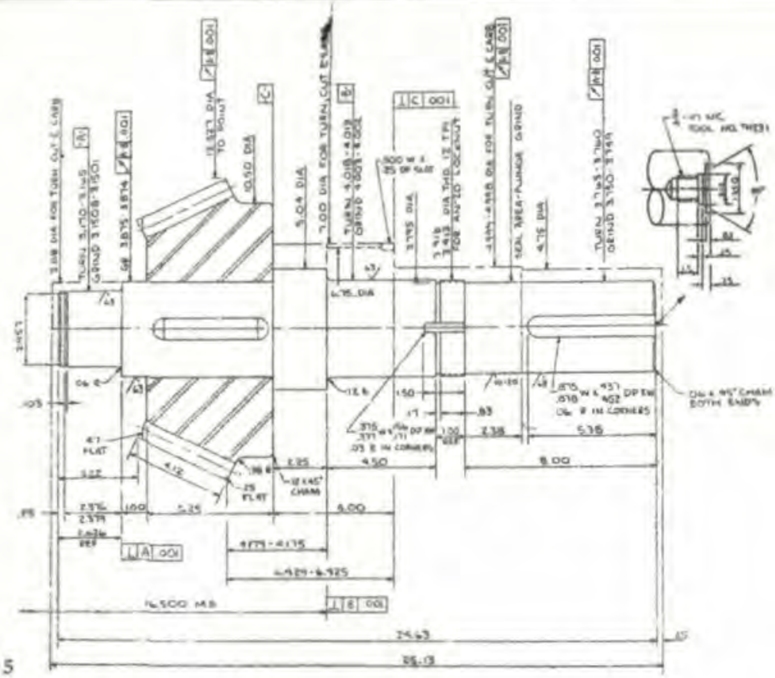


Fig. 5

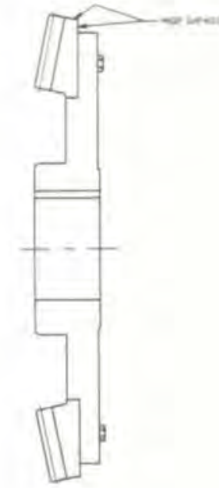


Fig. 6

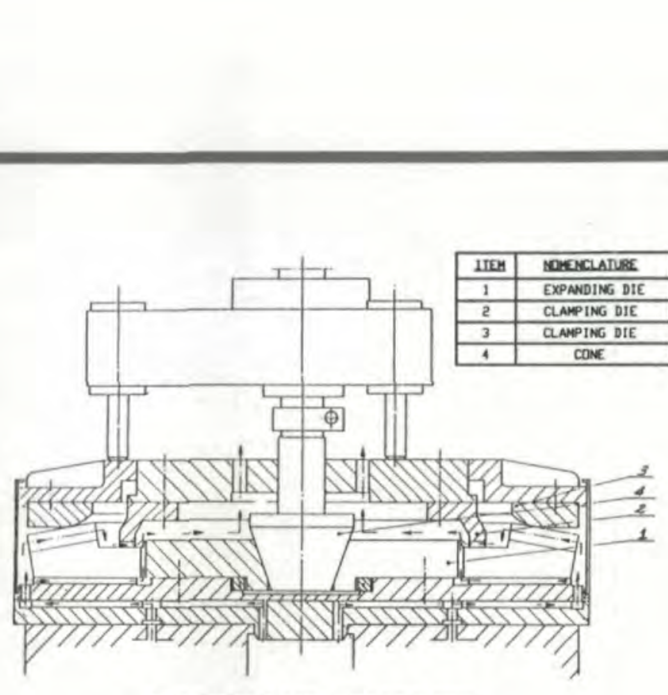
case of a bored pinion/gear, the subassembly with shaft should be done wherever possible to avoid concentricity and squareness problems (Fig. 5). Fig. 6 shows the subassembly of a ring gear and spider. In pinions, the one-piece design does offer some manufacturing advantages over the two-piece design. Also, small to medium size gears should be investigated for one-piece design, as there are some manufacturing advantages in the one-piece configuration.

Previously, gears were mostly designed as bored rings so that they could be die quenched, but hard cutting has changed the picture somewhat. Distortions in free quenching of small to medium size solid gears can be kept low with proper control. Hard cutting will remove the distortion from teeth. Caution must be used for any switch over from two-piece design to one-piece. There are many factors which affect distortions in heat treatment, such as material, blank configuration, fixturing in heat treatment, etc. Wherever possible, some experimental pieces should be manufactured to evaluate the situation before making the final decision, as excessive distortion is highly undesirable and can cause various problems at hard cutting.

Soft and Hard Cutting Summaries. A tooth cutting summary for a bevel generator provides machine set up data, cutter data, tooth measurements, and other tooth geometry information related to a specific spiral bevel set. Bevel hard cutting blades are very sensitive to proper feed and speed. Selection of correct amount of crowning stock allowance affects the overall quality and cutting times. Normally, in high batch production, a sample set or dummy set is always useful to fine tune the summary. In a jobbing or low batch atmosphere, a dummy set or experimental set may or may not be possible for various reasons; therefore, a jobbing atmosphere requires initial selection of all variables affecting tooth contact. The length and location of tooth contact should be based on factors, such as assembly conditions (overhung or straddle mounted members), tooth stiffeners, and loading, application, and past experience. Wherever possible, fine tuning of tooth contact can be achieved through load testing of bevel gears.

Heat Treatment Process Control. Excessive heat treatment distortions are highly undesirable for hard cutting of bevel gears for a variety of reasons, such as loss of case thickness, longer cutting times, tooth thickness problems, and mounting distance problems. Ring gears must be die quenched utilizing proper quenching dies. Fig. 7 shows a quench press. A pre-quench and temper operation of rough-turned blanks for large gears and pinions can assist in stabilizing the pieces during heat treatment. In the jobbing atmosphere, gears and pinions should be checked for distortion before releasing for final machining.

Finish Machining Operation. The finish machining of gears and pinions for hard cut bevel gears is very important. The runout and squareness and all other geometric tolerances of bearing diameters, proof diameters, etc. must be kept to less than 40% of the values allowed on the gear teeth. Any loose control in finish machining operations can add to distortion, leading to longer cutting cycles and various problems. It is vital that proof surfaces in both planes are indicated within specified values before proceeding with final machining. The big difference in the final machining of a lapped and a hard cut gear is that, in the event of a lapped set, the back face or mounting face is usually left as it is, while in hard cutting, it is ground or turned square to bore. In addition, it is critical that some extra material is left in the back of a hard cut



CROSS SECTION OF KLINGELNBERG QUENCH PRESS

Fig. 7

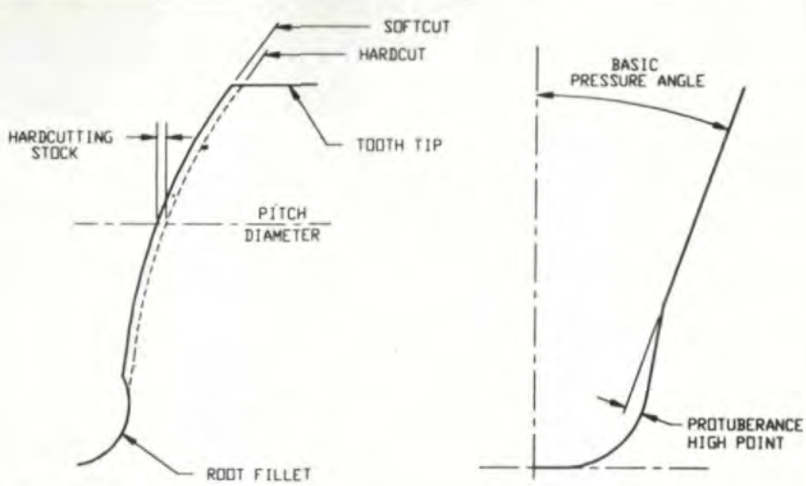


Fig. 8

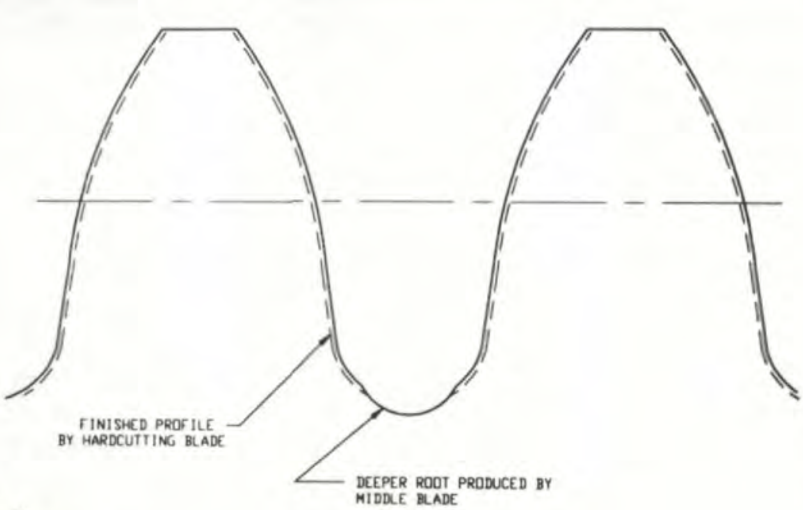


Fig. 9

gear at blank turning, which will then be removed at final machining. This will reduce the variations in mounting distances. In multiple pieces, consistency of the crown to back dimension is important for hard cutting cycles. Variation will cause adjustments for every piece on the machine, resulting in longer cutting cycles. Proper proof bands and surfaces must be created at final machining, with concern given to their location as well, so that they can be easily used for indication purposes at hard cutting.

Soft Cutting Blades. Fig. 8 depicts a blade with protuberance. Where ever possible, protuberance blades should be used. They will cut down hard cutting time, extend tool life, and reduce the possibility of steps in fillet. The use of customized protuberance blades is no problem in high batch production, but in jobbing or low batch production the picture is quite opposite. Amount and height of protuberance selection becomes difficult as blades are stretched to cover maximum range. Blades can still be obtained with protuberance selected very carefully, which will help hard cutting. Setting middle blades slightly deeper than side blades also helps in hard cutting and is a common practice in bevel cutting. Fig. 9 shows a fillet created with a deeper middle blade. Fig. 10 shows a blade for soft cutting.

Hard Cutting Blades. Bevel hard cutting began with the use of carbide inserts. Carbide inserts are clamped to steel bodies for coarse pitches and brazed for medium to fine pitch gears. In the beginning, low tool life with carbide inserts, frequent tool sharpening, insufficient experience, high cost, and many other factors kept hard cutting's use quite low. As hard cut bevel gears reached into the field, their performance in all aspects was the single most reason to increase the use of bevel hard cutting.

In the meantime, CBN inserts were introduced for hard cutting. The BZN (BZN is a trade mark of General Electric Company) compact blank is a combination of a layer of Borozon CBN (Cubic

You are cordially invited to learn from the best . . . ask the man who's been there

ITW Illinois Tools

Gear Tool Specialists
3601 WEST TOUHY AVENUE
LINCOLNWOOD, ILLINOIS 60645
708-675-2100
1-800-628-2220 In IL. 1-800-628-2221

"The Gear School"
OVER
30 YEARS
of Service to the Gear Industry.

The Society of Manufacturing Engineers (S.M.E.) has approved this School for Professional Credits toward the S.M.E. Recertification Program. Credits are awarded on the basis of one credit per content hour.

GEAR TRAINING PROGRAM

1. BASIC FUNDAMENTALS

1. **Gear History**
   - A. Cycloidal Teeth
   - B. Involute Teeth
   - C. Gear Cutting Machines
   - D. Gear Cutting Tools
2. **Gear Types**
   - A. Parallel Axis
   - B. Intersecting Axis
   - C. Skew Axis
3. **Gear Ratios**
4. **Involute Gear Geometry**
   - A. Nomenclature
   - B. Involutometry — Contract Ratio, etc.
   - C. Helical Gears — Lead — Helical Overlap
5. **Gear Tooth Systems**
   - A. Full Depth
   - B. Full Fillet
   - C. Stub Depth
6. **General Formulae**
7. **Mathematics — (I.T.W. Trig Book)**

2. HI SPEED STEELS

- A. Common Types
- B. Special Types
- C. Heat Treatment — Metallurgy
- D. Controls
- E. Surface Treatments
- F. Special Cases

3. CUTTING THE GEAR

1. **Forming**
   - A. Milling
   - B. Broaching
   - C. Shear Cutting
2. **Generating**
   - A. Shaping
     - a) Rack Type
     - b) Circular Type
     - c) Machine Types and Manufacturers
     - d) Schematic — Principles
     - e) Speeds — Feeds
     - f) Machine Cutting Conditions
   - B. Hobbing
     - a) The Hobbing Machine
     - b) Types and Manufacturers
     - c) Schematic — Differential and Non-Differential
     - d) Speeds — Feeds
     - e) Climb Cut — Conventional Cut
     - f) Shifting — Types
3. **The Hob as a Cutting Tool**
   - A. How It Cuts
   - B. Tolerances and Classes
   - C. Multiple Threads
   - D. Hob Sharpening and Control
   - E. The Effect of Hob and Mounting Errors on the Gear
4. **The Shaper Cutter as a Cutting Tool**
   - A. Know Your Shaper Cutters
   - B. Design Limitations
   - C. Sharpening
   - D. The Effect of Cutter Mounting and Errors on the Gear
   - E. Manufacturing Methods
5. **Tool Tolerance Vs. Gear Tolerance**
   - A. Machining Tolerances
   - B. Gear Blank Accuracy and Design Limitations

4. FINISHING THE GEAR

1. **Gear Finishing — Before Hardening**
   - A. Shaving
     - a) The Shaving Cutter
     - b) Types of Shaving — Conventional, Underpass, Diagonal
     - c) Crown Shaving
     - d) Shaving Cutter Modifications
     - e) Co-ordinating Tool Design— The Shaver and Pre-Shave Tool
     - f) Re-Sharpening
     - g) Machines
   - B. Rolling
2. **Gear Finishing after Heat Treat**
   - A. Honing
   - B. Lapping
   - C. Grinding
     - a) Methods — Formed Wheel-Generating — Threaded Wheel
     - b) Machine Types

5. GEAR INSPECTION

1. **Functional**
   - A. Gear Rollers
   - B. Gear Charters
     - a) Reading the Chart
     - b) Tooth-to-Tooth Composite Error
     - c) Total Composite Error
   - C. Master Gears
     - a) Tolerances
     - b) Designs
     - c) Special Types
2. **Analytical**
   - A. Size — Tooth Thickness
   - B. Runout
   - C. Spacing
   - D. Lead
   - E. Involute
3. **Automatic and Semi-Automatic**
   - A. How They Work
   - B. What Can Be Checked
   - C. How Fast
4. **Chart Interpretation — Analytical and Functional**
   - A. Reading the Charts
   - B. Which Errors Affect Other Elements
   - C. How to Correct the Error the Chart Shows

6. INDIVIDUAL INSTRUCTION AND SPECIFIC PROBLEMS OR PLANT TOUR

This Program is flexible and changed to meet the needs of each group.

The 4-day program consists of a coordinated series of lectures given by the Engineering, Production and Inspection staffs of Illinois Tool Works Inc. They represent over sixty years of experience in gear and tool specialization.

The sessions are conducted with a technique and approach that leads to interesing discussion and participation. Starting with the basic fundamentals, the program is directed into those areas of greatest interest and value to the people attending the particular session. The groups are kept small so that this object is readily accomplished.

As mentioned, the planned program lasts four days. One-half of the fourth day is for individual discussion of specific problems in a detailed manner with members of the Illinois Tool Works' staff.

More than 4,000 individuals from hundreds of companies representing manufacturing, engineering, inspection and management, have come to Chicago for these programs. They have been conducted on a monthly basis since 1958. Classes have also been conducted in Europe. We are certain that this well rounded program has helped all of them to a better job and also given them a better understanding of engineering, manufacturing and inspection.

All those attending are assigned to the same hotel. This promotes friendly contact and discussion of mutual problems and interests. Tuition for the course includes transportation from the hotel to ITW and back, one group dinner, all continental breakfasts and all lunches.

We hope we may include your company in one of our Training Programs.

ITW ILLINOIS TOOLS
A Division of Illinois Tools Works Inc.
1991 GEAR TRAINING PROGRAM
Four Day Seminars

January	14-17	May	13-16	September	16-19
February	11-14	June	10-13	October	14-17
March	11-14	July	15-18	November	11-14
April	15-18	August	12-15	December	2-5

TUITION FEE: $695.00

NOTE! Additional students, same company, same class $650.00

Includes the transportation from the hotel to ITW and back, one group dinner, hospitality meeting, continental breakfasts, and all lunches.

The Society of Manufacturing Engineers (S.M.E.) has approved this School for Professional Credits toward the S.M.E. Recertification Program. Credits are awarded on the basis of one credit per content hour.

For additional information contact:
ROBERT H. MODEROW
Manager, Training
708-675-2100
1-800-628-2220
In IL Call: 1-800-628-2221

CIRCLE A-20 ON READER REPLY CARD

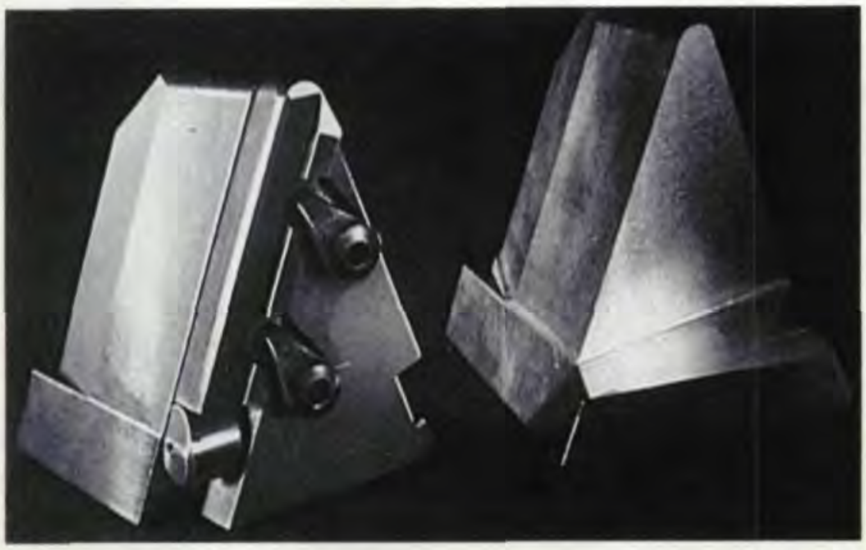


Fig. 10 — Courtesy of Klingelnberg Corp.

Boron Nitride) and a cemented tungsten carbide substrate produced as an integral blank using an advanced high pressure, high temperature process. The use of CBN inserts increased the tool life many times. Cutting times decrease appreciably as less sharpening is required. From a performance standpoint, the CBN inserts excelled considerably over the carbide inserts in every aspect, even though the price of the CBN insert is much higher than that of the carbide insert, tool price per gear did not rise because of improved tool life.

The CBN tools need much more careful sharpening, including the use of special machines, special fixtures, and diamond grinding wheels. The blades are sharpened on the cutting face. Extra care should be taken in storing, handling, and the use of CBN inserts. The correct feed, speed, and depth of cut is also very critical in the usage of CBN inserts.

Limitation of Bevel Hard Cutting

• Machine Accuracy. Bevel hard cutting and soft or rough teeth cutting are performed on the same or similar types of machines. The accuracy of the bevel generator reflects directly on the quality of gear teeth. Where more than one similar machine is available, it may be beneficial in the long run to use the better machine for hard cutting all the time.

• Single Indexing Versus Continuous Indexing System. Bevel generators with single indexing directly affect tooth spacing; whereas, continuous indexing offers significant accuracy in tooth spacing due to the natural hunting action between gear teeth and cutter blades.

• Multi-Start Cutter System. In cutting systems which utilize multi-start cutter heads, attention must be paid, so that the number of teeth is not divisible by the number of starts in the cutter head. Otherwise, the cutter head blade spacing can affect tooth spacing in hard cutting. In high batch production, this is never a constraint, as special cutter heads can be obtained for a set, but it can become a limiting factor in jobbing, where the exact ratio is a necessity. A multi-start cutter head can also be used as a single start cutter head, which will eliminate this problem; however, cutting times will increase.

• Fillet Finishing. In bevel grinding, the tooth fillets are completely ground, and the desired fillet radius is obtained by dressing the grinding wheel. In the bevel hard cutting process, the fillets are normally finished at soft cutting. Sometimes step problems may appear at hard cutting due to low or no protuberance, higher distortions, etc. The hard cutting blades are manufactured with a certain fillet radius, which should closely match with the roughing blade radius. During hard cutting, the fillet corners can be slightly skimmed with hard cutting blades, but any excessive fillet material removal compromises the tool life.

Summary

The hard cut bevel gears have performed very well in all applications. Hard cutting has improved load carrying capacity and has made quality bevel gears available to the industry at justifiable costs.

The improvement in large gears is even more noticeable as tooth grinding was not possible because of size. The introduction of CBN tooling has brought the tooling cost and cutting times to reasonable and economical values. Furthermore, consistency of hard cutting has made unmatched sets a reality under a controlled atmosphere and for certain applications. Hard cutting also provides gear teeth with the quality and surface finish of grinding without any possibility of any metallurgical damage. Finally, the utilization of CBN tools for hard cutting is being applied more frequently to parallel axis gears using shaper type machines.

Acknowledgement: *Reprinted with permission of the American Gear Manufacturers Association. The opinions, statements and conclusions presented in this paper are those of the Author and in no way represent the position or opinion of the AMERICAN GEAR MANUFACTURERS ASSOCIATION.*

References:

1. TRAPP. *"Quality Achievements In Spiral Bevel Gears By The HPG-Method"*, AGMA Semi-Annual Meeting, October, 1981.
2. LOFFELMANN, E. *"Hard Finishing Of Spiral Bevel and Hypoid Gears Using BZN Cutting Tools"*, AGMA Meeting Fall, 1985.
3. WIEGAND, R. *"Finish Machining Case-Hardened Spiral Bevel Gears To The Klingelnberg HPG-S Method."*