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Development of a Simple, Analytical Method to Optimize Machining Cycles for Non-CNC Gear Hobbing Machines

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Abstract

The purpose of this research project was to develop a simple, analytical method for the optimization of hobbing cycles on non-CNC gear hobbing machines. Such a method would allow manufacturers to optimize hobbing cycle times, reduce part costs, and improve productivity. There have been many advances in gear cutting tool technology. Because of these advances, the capabilities of modern cutting tools are beyond the capabilities of non-CNC machines designed more than fifteen years ago. The majority of the machines used today in gear manufacturing are of this vintage. The cycles on these machine tools are machine-limited, which is much more difficult for the gear manufacturer than when the machining cycle was tool-limited. Many more factors needed to be considered in order to optimize cycles. No simple analytical method exists to accomplish this.

DEVELOPMENT OF A SIMPLE, ANALYTICAL METHOD TO OPTIMIZE MACHINING CYCLES FOR NON-CNC GEAR HOBBING MACHINES

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CHAPTER I.

INTRODUCTION

There have been many advances in gear hobbing technology within the last fifteen years. These include the developments of powdered metal tool steels, special tool coatings, and a gradual change to water-based cutting fluids in gear cutting. According to K. Magee, tooling engineer with the John Deere Waterloo Works Gear Division, these developments have resulted in greatly improved tool life, and in reduced machining cycle times because of the ability of the cutting tool to withstand higher cutting speeds and heavier feed rates (personal communication, January 10, 1995). Prior to these improvements, gear hobbing machines were "tool-limited" which means that the cutting tool was the limiting factor in the machining process.

New Computer Numerically Controlled (CNC) hobbing machines have also been introduced within the last fifteen years. These machines have been designed to take advantage of the improvements in tooling technology, and are still tool-limited. Non-CNC hobbing machines, designed prior to the improvements in tooling technology, are no longer tool-limited. Instead, they have become "machine-limited". This means that the machine tool is the limiting factor in the machining process. Coping with a machine-limited cycle is much more difficult for the gear manufacturer than coping with a tool-limited cycle. More factors must be considered when determining the appropriate machining cycle. All current machining cycle guidelines are based on tool-limited technology (K. Magee, personal communication, January 10, 1995). Machine tool manufacturers have not devoted resources toward developing guidelines for older, machine-limited, hobbing machines. According to S. Peterson, regional sales manager for American Pfauter Limited, a manufacturer of gear hobbing machines; this is because hob manufacturers make their money selling new hobbing machines rather than helping gear manufacturers optimize machining cycles on older machines (personal communication, November 10, 1994).

Statement of the Problem

The problem of this study was that no simple analytical method for gear manufacturers was available to optimize machining cycles on non-CNC gear hobbing machines.

Statement of Purpose

The purpose of this research project was to develop a simple, analytical method for the optimization of hobbing cycles on non-CNC gear hobbing machines. Such a method would allow manufacturers to optimize hobbing cycle times, reduce part costs, and improve productivity. There have been many advances in gear cutting tool technology. Because of these advances, the capabilities of modern cutting tools are beyond the capabilities of non-CNC machines designed more than fifteen years ago. The majority of the machines used today in gear manufacturing are of this vintage. The cycles on these machine tools are machine-limited, which is much more difficult for the gear manufacturer than when the machining cycle was tool-limited. Many more factors needed to be considered in order to optimize cycles. No simple analytical method exists to accomplish this.

Statement of Need

The need for this research was based on the lack of a simple analytical method for the optimization of machining cycles on older, non-CNC, hobbing machines. Hobbing is the primary method used in industry today to produce gear teeth. It can be used either to rough form the gear teeth prior to finishing process, or for finishing the teeth in one operation. This process uses a specialized machine tool known as a hob, a hobber, or a hobbing machine. The cutting tool used is also called a hob. Generally, the only situations where hobbing is not used are when there is no clearance for the hob tool, or in cases when specially timed relationships need to be held with other features on the part (National Broach and Machine, 1972).

There have been many relatively recent advances in cutting tool materials, coatings and coolants used for hobbing. These improvements have made heavier cuts and higher speeds possible both on new machines and on existing older machines. The new hobbing machines are manufactured to have enough rigidity and power to take advantage of the improvements in tooling technology (S. Peterson, personal communication, November 10, 1994). The manufacturers of these new hobbing machines have also developed guidelines and programs to assist in the determination of the proper machine settings for optimum performance. Two of these programs are "G-Tech" (Gleason Works, 1989) and "Hob-Time" (American Pfauter Limited, 1992). The guidelines referenced in these programs are based on the limitations of the cutting tool. In these cases, the hobbing process is tool-limited (K. Magee, personal communication, January 10, 1995).

This was not the case with older hobbing machines designed prior to the advances in tooling technology. Today, these machines are mechanically limited due to lack of power, lack of rigidity, and the basic design of the machine. The machining cycles are machine-limited rather than tool-limited. Optimizing cycles on existing older machines was not very well understood, and could be quite complicated. The original guidelines provided by the manufacturer have been out-dated by the improvements in cutting tool technology. This leaves the owners of older machines to optimize machining cycles to the best of their ability. This process was best described as "trial and error" and was based on the previous experience of the gear manufacturer. Using this method, different machine settings were tried until the process produced a quality part and the cutting tool did not show excessive wear. At this point the cycle was considered "optimized". However, this process had several drawbacks (K.Magee, personal communication, January 10, 1995).

The first was that the machining cycle is seldom optimized, only improved. A better cycle was achieved, but it was not always optimum for the machine or for the cutting tool. According to W. M. Christofferson, quality engineer for purchased gears at the John Deere Waterloo Works (personal communication, June 6, 1994), another drawback was that the capabilities of the hobbing machines were not addressed in an analytical manner. Judgment and a "best guess" were used. Usually the cycle was over-conservative, which underutilized the hobbing machine and the cutting tool. Occasionally, the cycle was over-aggressive which could over-work the machine or the cutting tool, and could result in expensive repairs or premature tool wear.

To stay competitive in the market place, gear manufacturers need to be as efficient as possible (W. M. Christofferson, personal communication, June 6, 1994). One way to improving efficiency was to optimize hobbing cycles on existing non-CNC hobbing machines.

Research Questions

The following questions were to be answered in this study:

1) Can a simple analytical method be developed to optimize hobbing cycles on non-CNC machines?
2) What analytical criteria can be used to determine when the machining cycle is optimized?
3) Will this analytical method be useful for many different types of hobbing machines?
4) What are the limitations of the proposed analytical method?

Assumptions

The following assumptions were made in conducting this study:

1) The first assumption was that the all the components of the hobbing operation were in good condition: the cutting tools had been properly sharpened and coated, and that no mechanical or electrical problems existed in the hobbing machine.
2) The second assumption was that no significant differences existed between similar hobbing machines.
3) The third assumption was that the theoretical calculations used to determine the cutting torque and horsepower closely approximated the actual cutting process. The chip load, and chip formation for the hobbing process are very complex and significantly different than milling or turning processes. The computer programs and calculations that exist today are somewhat proprietary in nature, and are not shared with the users of these programs. As a result of this, the assumptions and limitations of the calculations could not be thoroughly analyzed before conducting this study.

Delimitations

The research conducted to develop a method of optimizing hobbing cycles on non-CNC gear hobbing machines was delimited by the following:

1) This study developed a generic method with general criteria for the optimization of hobbing cycles, with the exact limits for each of the criteria dependent on the type of hobbing machine. The limits for each of the criteria were not developed for all types and models of hobbing machines. This study was delimited to only the Barber Colman 16-15 vertical hobbing machine. This machine was chosen based on: the availability of this machine for experimentation; the acceptance of this machine as one of the better non-CNC hobbing machines in use today; and the need of the researcher to optimize machining cycles on this machine.

2) The criteria for the analytical method developed in this study was delimited to optimizing the machining cycles for helical gears with a diametrical pitch of approximately 5, and a helix angle of 15 to 25 degrees. It was possible to extend the general method with other criteria for cycle optimization to include other families of gears, but because of the wide range of gears, it was expected that the criteria for each range would be substantially different. This family of gears was chosen because of the availability of gears with this pitch and helix angle for experimentation, and the need of the researcher to optimize machining cycles for these gears.
3) The criteria for the analytical method was delimited to pre-shave hobbing using a single thread hob. There are two general types of hobbing: rough and finish. Rough hobbing is used to rough cut the gear teeth prior to another finishing operation. One of the most common finishing processes for gears is shaving. Hobbing prior to shaving is most commonly known as "pre-shave hobbing". Finish hobbing produces the final form of the gear teeth, with no subsequent operations. The "threads" on the hobbing tool determine the relative rates of rotation between the cutting tool and the work piece. Each thread on the hob will advance the workpiece one tooth for each rotation of the cutting tool. Hobs with a single thread produce the smallest cutting force for a given feed rate, and will usually produce the highest quality gears (Cluff, 1992). They are also the most common type of cutting tool used on non-CNC machines. The criteria developed was delimited to pre-shave hobbing using single thread hobs because this is the most common type of hobbing performed on the coarse pitch gears when using non-CNC machines.
4) This study developed general criteria for the determination of cycle optimization, with the exact limits for each of the criteria dependent on the gear manufacturers operation and situation. The limits for each of the criteria were not developed for the many

different operations and situations. These were delimited to only the manufacture of pre-shave, coarse pitch helical gears at the John Deere Waterloo Works Gear Division.

Procedure

The procedure for this research study consisted of the following:

1) A review of current literature was performed to determine and identify: A) the capabilities of modern cutting tools; B) the criteria for cycle optimization; C) the measurable factors which affect the hobbing cycle and the quality of the resulting gears; and D) how these measurable factors relate to non-CNC hobbing machines.
2) A general analytical method for the optimization of hobbing cycles was developed which could be applied to many different types of hobbing machines. From the review of literature, the tool-limiting factors were identified, as well as the guidelines associated with optimizing hobbing cycles on modern CNC machines. Then, limiting factors associated with non-CNC machines were identified. Next, all of these factors were combined and applied to non-CNC machines. However was recognize that the machine, rather than the cutting tool, was the limiting factor on the non-CNC machines. In this machine-limited situation, some of the factors on tool-limited machines did not apply, and there were other factors associted with the older non-CNC machines which needed to be included.
3) The general analytical method was applied, and specific limits were developed, for the Barber-Colman 16-15 hobbing machine cutting pre-shave, coarse pitch helical gears. These limits were based on what is known about optimizing hobbing cycles on CNC machines, but were tailored to the non-CNC Barber-Colman machine based both on the capabilities of the cutting tool, and the limitations imposed on the cycle by the structure and capabilities of the machine. Some testing was required for the development of specific limits. One factor known to be a limitation on non-CNC machines was the torsional stiffness of the spindle and drive train of the machine. At some torque level,

the torsional stiffness of the shafts and gears acting as a system in the machine can be exceeded. When this happens they will start to deflect. These deflections have a negative effect on the quality of the gear. Specifically, the gear lead started to show a bow, or deviation from the desired gear lead. This is also known as "wind-up". Theoretical calculation of the torsional stiffness would have been very difficult because of the complexity of the shafts, gears, bearing etc. acting as a system in a non-CNC hobbing machine. It would also be different for other types of machines. The user of the hobbing machine is primarily concerned with the torque level at which the hobbing machine will start to wind-up. To determine this limit for the Barber-Colman 16-15 hobbing machine a series of tests were conducted to determine the limit for the torque at which the components in the machine started to deflect.

4) Confirmation of method and limits was performed by conducting a series of tests and observing the resulting tool wear and gear quality. A series of tests were conducted. Each series of tests varied the limits for the method criteria around the predicted optimum settings. Not all criteria were varied for all of the tests. The resulting gear quality and tool wear for each series of tests were measured and compared to determine if the prediction of the criteria for the developed method was correct.

Definition of Terms

Manufacturing, and specifically gear manufacturing, uses many unique terms. Below is a list of terms and their definitions which are needed to help in the understanding of this research paper.

Chatter : Severe reoccurring vibration between the tool and the workpiece during a cutting cycle. The vibrations can cause gouging of the workpiece and poor gear quality.

Chatter also causes increased wear on the machine and cutting tool. (Giddings & Lewis Incorporated, 1986)

Cutting Horsepower : The maximum horsepower consumed by the cutting tool during the cutting process (G-Tech, 1989).

Cutting Torque : The maximum torque generated by the cutting tool during the cutting process (G-Tech, 1989).

CNC : Computer Numerical Control; A method of controlling machine-tools and other processes using microprocessors; adapted to gear manufacturing in the early 1980's (Cluff, 1992).

Coarse Pitch Gears : Gears with a diametrical pitch of 2 to 16 (Dudley, 1991).

Diametrical Pitch : The number of teeth per unit of pitch diamter; used as a standard measure of the depth, or coarseness, of gear teeth. The diametrical pitch is expressed by the equation: $P=N/d$; where P is the diametrical pitch, N is the number of teeth in the gear, and d is the diameter of the gear (Dudley, 1991).

Gear Lead : A measure of the actual helix angle of a gear compared to the desired helix angle. Also know as simply "lead" (National Broach & Machine, 1972).

Helical Gear : A type of gear where the gear teeth are at an angle to the axis of rotation of the gear (Deutschman, Michels and Wilson, 1975).

Helix Angle : The included angle of the teeth on a helical gear relative to the axis of rotation (Deutschman, Michels and Wilson, 1975)..

Hob : 1) The cutting tool used to generate gear teeth on a hobbing machine.

2) The machine used to generate gear teeth using the hobbing process.

Hobbing : The process of generating gear teeth by controlling rotational index between the work piece and a special multi-tooth cutter known as a hob (National Broach & Machine, 1972).

Hobbing Machine : The machine used to generate gear teeth using the hobbing process.

Machine-limited : A machining process which is limited by the capabilities of the machine-tool.

Pitch : A general term used to mean the diametrical pitch (Dudley, 1991).

PIV Drive : A type of mechanical variable speed drive used in machine tools. It consists of a pair of variable diameter pulleys connected by a continuous chain of constant length. Output speed is varied by adjusting the diameters of the pulleys (Barber Colman Company, 1980).

Pre-Shave Hobbing : Hobbing of gear teeth to generate the rough tooth form. Stock is left on the teeth for a finishing operation, usually shaving, to bring the gear teeth to the correct size (National Broach & Machine, 1972).

Surface Footage : The number of linear feet per minute at the circumference of the cutting tool. For hobs the equation is: 3.14159 x tool diameter in ft. x spindle RPM (Cluff, 1992).

TIN : Titanium Nitride; a tool coating commonly used on hobs. Gold in appearance, this coating is extremely hard, which reduces wear and improves tool life (Maddock, 1994).

Tip Radius : The radius on the edge of a cutting tool. In the case of a hob, it is the radius on the top of the cutting teeth. The tip of the hob forms the root of the resulting gear (National Broach & Machine, 1972).

Tool-limited : A machining process which is limited by the capabilities of the cutting tool.

Tool Coating : A thin layer of a special material applied to the cutting edges of a cutting tool. Common coatings include TIN, various extremely hard oxides, Cubic Boron Nitride, & Diamond (Maddock, 1994).

Torsional Stiffness or Torsional Rigidity : The ability of a machine as a system (gears, shafts, bearings, housings etc.) to resist deflections under torsional loading (Deutschman, Michels and Wilson, 1975).

Wind-up : A term used in gear manufacturing to indicate that the torsional stiffness of the hobbing machines has been exceeded, and the quality of the gears manufactured is starting to deteriorate (Cluff, 1992).

CHAPTER II.

REVIEW OF LITERATURE

The following sections identify the advances in cutting tool technology related to hobbing, and the improved coolants used today. Also, CNC and non-CNC hobbing machines are discussed, and the general limitations of the non-CNC machines explained.

Advances in Cutting Tool Technology

There have been many advances in cutting tool materials and coatings within the last 15 years. These advances include powdered metal technology, advanced tool steel materials, and the development of titanium nitride (TIN) coatings.

Today, powdered metal tool steel is used to manufacture hobs and other cutting tools. It has made stronger, less brittle cutting tools possible (Maddock, 1994). The material is much more uniform, eliminating the metallurgical flaws found in traditional tool steels. This makes the tools much stronger and able to withstand higher cutting loads without breaking. This uniform structure also hardens during heat treatment with fewer distortions. This makes the resulting tools much more accurate and able to produce higher quality gears. Additionally, advanced tool steels have also been developed to withstand greater forces and provide longer tool lives

TIN coating of cutting tools has increased the abrasive wear resistance of cutting tools. A thin layer of TIN is applied to the cutting surfaces of the tool. TIN is harder and more wear resistant than the material of the cutting tool. This coating has made higher cutting speeds, and heavier cuts possible. Empirical studies cited by Cluff (1992) show that the maximum practical surface footage for an un-coated hob can be determined by the Equation 1.

(1)

In this equation, BHN is the Brinell hardness of the gear blank. For most gear materials the resulting surface footage is 220 Surface Feet per Minute (SFM). Similar studies conducted for TIN coated hobs show that the maximum practical surface footage is determined by the Equation 2.

(2)

For the same gear blank materials, this surface footage is 330 SFM. This represents a 50% possible increase in cutting speed due to the TIN coating of cutting tools.

Improved Coolants

Another recent advancement in hobbing has been the switch from traditional cutting oils to water-based coolants. Cutting oils provide good lubrication for the cutting process, but do not have a high thermal capacity, nor do they have a high thermal conductivity. According to the 64th edition of the CRC Handbook of Chemistry and Physics (Weast, 1985), the thermal capacity of a substance is the amount of heat required to raise one unit mass of the substance one degree. Water-based coolants have approximately 2.2 times the thermal capacity of oils (Incroprea and DeWitt, 1985). Thermal conductivity is the time rate of heat transfer. Water-based coolants have approximately 4.2 times the thermal conductivity of oils. (Incroprea and Dewitt, 1985). Heat is generated in the cutting process and needs to be removed from the cutting tool and work piece. Excessive heat can cause failure of the cutting tool. Today, water-based coolants have additives to provide lubrication for the cutting process, and they have high thermal capacity and conductivity. These abilities remove heat quickly from the cutting tool and extend tool life, allowing higher cutting speeds and heavier cuts. Studies done in 1992 and 1996 at the John Deere Waterloo Works demonstrated a 10 to 100 percent increase in tool life by changing from cutting oils to water-based coolants (K. Magee, personal communication, January 10, 1995).

It should be mentioned that the use of water-based coolants in gear hobbing is somewhat controversial and not universally accepted. Many gear and hobbing machine manufacturers oppose the use of water based coolants in hobbing, claiming that it can cause wear and corrosion in the machine. They further claim the use of water-based coolants results in higher maintenance costs and decreases the useful life of the machine. The concern is that coolant will leak into places where it does not belong, causing electrical component to fail, rust and corrosion. It is also true that some seal materials and other components of hobbing machines chemically deteriorate with constant exposure to some water-based coolants. These drawbacks can be countered with modern rust preventative additives in the coolant, and changing to other sealing materials or coolants where a specific coolant causes materials to deteriorate. At the John Deere Waterloo Works, water-based coolants have been used in almost all of the vertical hobbing machines successfully for the last three years. At that facility, the benefits of the waterbased coolants out-weigh the few problems which have resulted from their use (K. Magee, personal communication, January 10, 1995).

Optimizing Hobbing Cycles

The general definition of the optimum pre-shave hobbing cycle is production of quality gears as quickly as possible with the best possible tool life. To achieve this a compromise between different factors must be achieved.

According to the Gear Hobbing Mechanical Data Book (John Deere Waterloo Works, 1978), tool life for a hob is somewhat different than other modern cutting tools. Only a small portion of a hob is actually used to cut a gear, even though the hob itself may be several inches long. The holder of the hob, known as the head, has the ability to shift back and forth in the machine. When the hob is placed in the machine, the head is positioned so that one end of the hob is used first. Then, after each gear is cut the head is "shifted" toward the other end of the hob. This allows new cutting surfaces to be used for the next gear, and the used cutting surfaces to become inactive. The linear distance the head is shifted between each gear and the usable length of the cutting tool defines the tool life. (The usable length is divided by the amount of the shift to determine the number of pieces per cutting tool). The size of the shift is determined by the severity of the cut. If heavy cuts are taken in wide gears, the shift is large. If light cuts are taken, or the gears are thin, the amount of the shift can be quite small. In fact, on very light cuts, instead of the head shifting after every piece, it can be shifted after multiple pieces. The exact size of the shift is determined from visual examination of the amount of wear on the tips and flanks of the cutting tool. Ideally, a light pitting on the face just under the tip is desired. On the flanks, slight wear is desired, but no chipping of the edge of the teeth. The size of the hob shift is adjusted until the correct amount of wear is achieved for the machining cycle feeds and speeds (K. Magee, personal communication, January 10, 1995).

The optimum cycle is a compromise between cycle time and tool life. If the cycle is too aggressive, poor tool life will result. If the cycle is too conservative, tool life will be very good, but productivity will suffer. Additionally the lot size and configuration of machines must be considered. Ideally, the lot size will match the tool life. This situation maximizes the number of gears from each hob, and minimizes the number of tool changes. If this is not possible, according to W. M. Christofferson, quality engineer for purchased gears at the John Deere Waterloo Works (personal communication, June 6,1994), it is then best to limit the number of tool changes required to once per shift. This minimizes the interruptions during the day, and allows maximum productivity.

If the hob is in battery with other machines in a sequential operation, the cycle times of all the machines in the operation must be considered. If one of the machines is slower than the hob, very aggressive cycles on the hob do not benefit the operation because the hob must then wait for the other machines. In this situation it is best to slow the hobbing cycle, and maximize tool life. If the hob is the slowest machine in the operation, then reductions in cycle time can greatly benefit productivity, as long as tool life remains acceptable. Each situation will be different and needs to be thoroughly examined by the manufacturing engineer.

CNC Hobbing Machines

New CNC hobbing machines are designed with enough rigidity and power to take full advantage of the improvements in cutting tool technology. Independent motors are used for the spindle drive, the table drive and the feeding mechanism. These drive trains have fewer and stiffer mechanical components, which result in fewer unwanted deflections and vibrations during machining. The cutting tool is the limiting factor for these machines.

Optimizing Hobbing Cycles on CNC Machines

CNC hobbing machines are tool-limited. As a result, the limits of the machining cycle are defined by the limitations of the cutting tool. The factors used to determine if the machining cycle is optimum on CNC equipment have been identified by manufacturers of hobbing machines and cutting tools. These generally are: the surface footage of the rotating cutting tool, the cutting horsepower, and the chip load. These factors can be calculated using computer programs. Using these programs, the geometry of the hob and the gear are entered along with speeds, feeds and other parameters for the machining cycle. This allows several different machining cycles to be quickly compared before any are attempted on the machine tool (G-Tech, 1989).

For a modern TIN coated cutting tool the limits for these factors generally are:

- 330 surface feet per minute.
- 10 cutting horsepower
- 0.120 inches maximum chipload.

Tool life is determined from the shift distance and length of the hob as discussed on page 14. The gear manufacturer adjusts the cycle to achieve an acceptable tool life for the operation. For this study "G-Tech" (Gleason Works, 1989) was used to calculate the cycle factors.

Non-CNC Hobbing Machines

Non-CNC hobbing machines were designed prior to most of the advances in cutting tool technology. At the time of design, the hob cycles were tool-limited. The recent advances in cutting tools and coolants have changed this. Today the non-CNC hobbing machine is usually the limitation for optimizing the hob cycle. The factors which limit these machines are: spindle speed, rigidity, power, and torsional stiffness.

Spindle speed refers to the maximum possible speed of rotation for the hob spindle. This speed determines the surface footage for the machining cycle. For example, a TIN coated hob can operate at a surface footage of 330 SFM. If a four inch diameter hob is used, this surface footage requires a spindle speed of 300 rpm. According to the Gear Hobbing Mechanical Data Book (John Deere Waterloo Works, 1978) many hobs still in use today were designed with a maximum spindle speeds in the range of 240 to 260 rpm. Before the introduction of TIN coating, these spindle speeds were adequate. However, today the spindle speed limits productivity.

Rigidity refers to the overall stiffness of the machine tool, including the fixtures and arboring used to hold the workpiece. It can be thought of as the resistance to deflection and vibration. If the hobbing machine or fixtures deflect during the cutting cycle, the quality of the gear is seriously affected. If vibrations, also known as "chatter", occur during the cycle, the quality of the gear is similarly affected. Deflections and vibrations are greatly influenced by the forces developed during cutting. Modern cutting tools can generate and withstand greater forces than older non-CNC hobbing machines were designed to withstand. As a result, the lack of rigidity of these older machines can limit productivity.

In a similar manner, the total power of the machine can limit productivity. Non-CNC hobbing machines have a single main motor. The motor provides the power to the table drive and the hob spindle. A schematic of a typical internal drive train for a non-CNC hob is shown in Appendix A. These drive trains require considerable energy to operate. In contrast, CNC hobbing machines have independent motors for each of these functions. The spindle drive motor alone is usually 15 HP or more. In contrast, the motor for non-CNC machines is usually 15 HP or less. An example is the Liebherr model 401 hobbing machine, which has an 11.2 HP drive motor. A machine cycle with a cutting power of 5.5 HP has been shown to stall a Liebherr 401. In contrast, cuts of 11+ HP are possible on modern CNC Gleason model 782 hobs.

Torsional stiffness refers to the ability of the internal shafts, gears, bearings and housings in a machine tool to withstand torsional (twisting) loads without deflection. According to Deutshman, Michels & Wilson (1975), if the torsional limit of a shaft is exceeded, the shaft will slightly twist. The same is true for the rest of the components of the hobbing machine. In hobbing these deflections are known as "wind-up". If it occurs during the machining cycle, the quality of the gear can be seriously effected. To eliminate the effects of wind-up, the feed rates can be reduced, or a second cut can be added to the machining cycle. In this case, the first cut is a roughing cut, leaving only 0.5 mm of stock to be taken off on the second cut. In either case; the machining cycle time is increased and the productivity of the hob is reduced because of the lack of torsional stiffness.

CHAPTER III.

DEVELOPMENT OF THE GENERAL ANALYTICAL METHOD

Based on the review of literature, the general method for the optimization of machining cycles on non-CNC hobbing machines consists of the several steps. These include:

1) Define the optimum cycle for the given manufacturing situation.
2) Optimize the cutting speed.
3) Maximize the practical cutting horsepower.
4) Maximize the practical cutting torque.
5) Analyze the resulting cycle and approximate tool life.

Define the Optimum Cycle for Manufacturing Situation

As identified in the review of literature, optimization of the machining cycle is generally defined as the manufacture of quality gears as efficiently as possible with the best possible tool life. In the case of non-CNC hobbing machines, gear quality and cycle time are usually the limiting factors for cycle optimization. In most situations, the cycle is optimized when it produces a quality gear as quickly as possible.

This is because of the severe limitations imposed on both gear quality and cycle time by the capabilities of the non-CNC hobbing machine. Typically, gear quality will be the first affected; most often due to a lack of torsional stiffness in the hobbing machine which negatively affects the lead of the gear. Other limitations to the cycle time include the spindle speed and the rigidity of the machine as discussed in the review of literature.

If the hob is in a manufacturing cell with other machines, the cycle time on the hob may not be the most important consideration for cycle optimization. However, this is not often the case. Typically, the hobbing cycle is the longest machining process in the manufacturing of large coarse pitch gears, and any reductions in cycle time are an improvement in productivity (K. Magee, personal communication, January 10, 1995). Tool life is usually considered only after gear quality and overall cycle time. Generally, non-CNC machines can not use modern cutting tools to the limits of their capabilities, and tool life is not a major consideration. Exceptions to this include coarse pitch gears with wide face widths. These gears require a great deal of material removal to form the gear teeth. This situation can cause a great deal of wear on the cutting tool by the end of one machining cycle. In these situations, lot size and the number of cutting tool changes should be considered as discussed in the review of literature.

Optimize the Cutting Speed

The next step for optimizing the hobbing cycle is to optimize the cutting speed for the manufacturing situation. This will typically be a compromise between the limitations of the cutting tool and the machine tool. The limits of TIN coated cutting tools were discussed in the review of literature. In most situations, the hardness of the gear blank material will be approximates 190 BHN (Maddock, 1994). Using the equation 2 from the review of literature, the resulting surface feet per minute of the cutting tool will be 330. For a typical 4 or 5 inch diameter hobbing tool, this will be in the range of 245 to 300 hob spindle rpm. Maximum designed spindle rpm for many non-CNC hobbing machines still in use today is in the range of 240 to 300 rpm. However, many of these machines no longer perform at these speeds. It is not uncommon to find that machines with a maximum rated rpm of 300 are only capable of speeds of 265 rpm (K. Magee, personal communication, January 10, 1995). It may also be undesirable to run these older machines at the maximum possible speed. One common reason for this is to avoid over working the motor and causing premature failure. These machine limitations usually define the optimum cutting speed on non-CNC machines.

According to K. Magee (personal communication January 10, 1995), another limitation to the cutting speed which must be considered is the tip radius of the cutting tool.

Hobs with a very small tip radius can fail at cutting speeds which are considered "normal" for most cutting tools. It is often necessary to reduce the cutting speed for these gears in order to maintain acceptable tool life. This is very common for gears with a 14.5 degree pressure angle. This can also be the case with wide, coarse pitch gears. By slowing the cutting speed, it is often possible to greatly improve tool life for these gears. These are special situations which need to be dealt with individually.

Another reason to limit the cutting speed may be lack of rigidity in the machine or fixturing. If the machine or fixturing lacks the required rigidity to withstand the cutting forces generated during the machining cycle, chatter may develop. Chatter conditions are hard on the machine and the cutting tool. There are three general ways to eliminate this chatter from the cutting process: improve the rigidity of the system, reduce the cutting speed, or change the feed rate. Improving the rigidity is the best solution, but on older, "loose" hobbing machines, this is not always possible without a major overhaul of the machine tool. Increasing or decreasing the feed rate may also change the forces on the cutting tool and work piece, and eliminate the chatter. This solution does not always give the most consistent results. Machine to machine variations are very common; and variations can also occur due to changes in the hardness and metallurgy of the gear blanks from one lot of material to the next. Decreasing the cutting speed is often the best solution to chatter problems. In this way, lack of rigidity can limit the cutting speed in some situations.

<u>Maximize the Practical Cutting Horsepower</u>

The horsepower of cut, or cutting power, can be limited by the same factors which affect the cutting speed: the limits of the cutting tool, the machine tool, or the need for improved tool life.

According to tooling and machine manufactures, modern TIN coated cutting hobbing tools can withstand a practical limit of approximately 10 horsepower (G-Tech, 1989). Experience with CNC hobbing machines has shown that in some situations, they can withstand over 11 horsepower, but according to S. Sneider, hobbing machine operator at the John Deere Waterloo Works (personal communication, February 25, 1995) tool life rapidly deteriorates at these high cutting powers. In a similar manner, CNC hob manufacturers recommend a safe cutting power limit for their machines. This is to prevent over working the main drive motor, or possibly damaging other components in the machine drive train.

This logic can also be applied to non-CNC hobbing machines. There is theoretically a maximum safe cutting horsepower for each type of machine. This is an extremely important concept to apply to non-CNC hobbing machines. At the time of manufacture, the drives in these machines could handle more horsepower than the cutting tools. As a result, manufacturers did not recommend a horsepower limit. Additionally, there was no easy method to determine the actual cutting power, so that method of defining the limits of the cutting tool did not exist. Today, the cutting tools can withstand more horsepower than the non-CNC machine can safely deliver. If this "limit" is exceeded, the possibility exists that the machine can become damaged, or wear out at a much greater rate.

To optimize the hobbing cycle on non-CNC machines, the maximum safe cutting horsepower needs to be determined. This can be accomplished one of two ways: analytically, or empirically. Using the analytical method, a schematic of the drive train in the machine is used to determine the frictional power losses in the machine due to the bearings, gears, worm drives, etc. A few assumptions may be necessary to accomplish this. From design manuals, it is possible to determine the percent efficiency for each of the different components of the drive train. For example, spur gear drives are generally 98% efficient, bearings are generally 99% efficient, and worm gear drives vary depending on the speed of operation from 97% to as low as 50% (Deutschman, Michels & Wilson, 1975). Due to wear in older machine tools, it is best to assume higher losses if a range of values is given. Once the losses in the drive train are determined, they are subtracted from the original designed horsepower of the machine to determine the available cutting power. This value is then decreased some amount as a factor of safety to prevent over working the main drive motor. Typically a 5 or 10% reduction is sufficient. This will give the maximum theoretical safe cutting power.

The second way to determine this value is empirically, and will depend on the resources available. With this method, the power draw of the motor is measured during the cutting cycle. The cutting power is calculated for the machining cycle using one of the computer programs discussed earlier. The difference between the cutting power and the actual power draw is the losses within the drive train of the machine. These values can then be used to determine the efficiency of the machine. This value is used with the maximum designed horsepower of the machine and any desired safety factors to determine the maximum safe cutting power for the non-CNC hobbing machine.

Maximize the Practical Cutting Torque

As discussed in the review of literature, torsional stiffness can limit the machining cycle on non-CNC hobbing machines. This is also know as "wind-up" or "break-out". It effects the quality of the resulting gear. It is seen in the lead of the gear as a bow or "dog leg". This is demonstrated on the next page in the sample lead inspection traces in Figures 1 and 2.

Figure 1 is representative of the desired gear lead, which is an approximately straight line on the graph paper. The "waviness" in the lead are the feed marks left on the flank of the gear by the hob. These are averaged out during interpretation of the graph. Figure 2 shows evidence of torsional wind-up during the cutting cycle, which is apparent from the "bow" in the trace. The lead trace is representative of the surface of the gear along its axis. The trace with wind-up indicates that there are high and low points across the face of the gear, which can negatively effect the quality of the finished gear, and reduce tool life for the finishing operation.

Figure 1. Sample of desired lead trace.

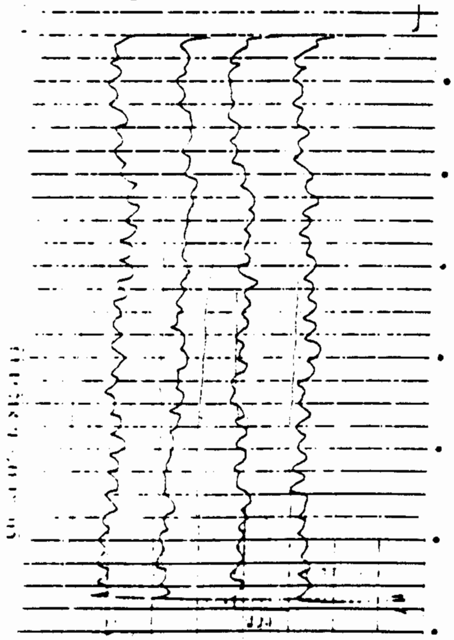
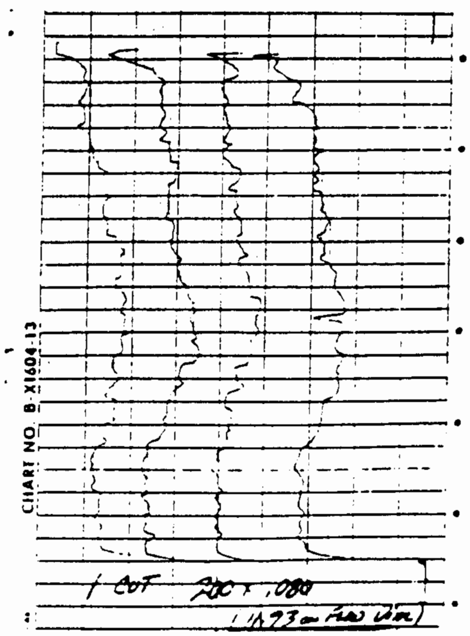


Figure 2. Lead trace illustrating wind-up.



As previously discussed, the bow in the lead is caused by deflections in the drive train of the machine. It can be caused by torsional deflections in the spindle or other shafts, by deflections of gear teeth, by wear or movement in the bearings, or by deflections in the bearing supports or housing of the machine under load. It is possible by measurements and calculations to determine which components of the drive train are deflecting, and at what cutting torque this will occur. It may then also be possible to repair the machine and improve the torsional stiffness. Such calculations, measurements and repair procedures are routinely performed by machine manufacturers during the development of new machine tools, but they are beyond the capabilities of most gear manufacturers who are working with older machines. The best way for gear manufacturers to deal with the problem of lack of torsional stiffness is to experimentally determine the cutting torque at which torsional deflections begin to occur for a given type of gear and use this value as a cutting torque limit.

A simple experimental procedure to determine the torsional limit for a machine is to gradually increase the feed rate for a selected group of gears and inspect the lead of the resulting gears. The cutting torques for each machining cycle are also calculated. When torsional windup appears in the gear lead, the torsional limit has been reached. This procedure must be performed for each type or group of gears to be manufactured on the hobbing machine. Establishing the trend is necessary because of assumptions made in the calculation of cutting torque by the different computer programs available. From experience at the John Deere Waterloo Works (K. Magee, personal communication, January 10, 1995), it is known that no exact limit can be determined from the calculations alone. The equations and programs used to calculate cutting torque are proprietary in nature, and the sources of error can not be determined exactly, but once a trend is established for a group of gears, this limit can be applied to similar gears. This torsional limit is good for only the type and model of hobbing machine which was used for the testing. Similar testing procedures will need to be conducted to determine the torsional limit for other types of machines, or for other families of gears.

Analyze the Resulting Cycle and Approximate Tool Life

Once the desired machining cycle parameters have been established to optimize the cutting speed, horsepower, and torque for a specific group of gears and model of hobbing machine, the next step is to cut a gear using this cycle and analyze the results. After the gear is cut, it is inspected using a lead and profile machine to determine the resulting quality. If the quality is acceptable, several more gears are cut and the hobbing tool is inspected to determine the amount of wear. Light pitting just below tip of the tooth on the cutting tool and slight wear on the flanks of the teeth indicate that the shift distance are appropriate for the machining cycle. If more wear is seen on the teeth of the cutting tool, the shift distance needs to be increased for the machining cycle; if little or no wear is seen, the shift distance can be decreased. Appendix B shows examples of light, desired, and excessive cutting tool wear. After the shift distance is adjusted based on the initial examination of the tool, several more gears are cut and the cutting tool is re-examined. Once the wear is appropriate for the machining cycle and shift distance, the tool life is calculated by dividing the active length of the cutting tool by the shift distance to determine the number of pieces per tool.

If the resulting gear quality is unacceptable, adjustments need to be made to the machine cycle parameters. This usually indicates that one of the assumptions made in the establishment of these parameters is incorrect. If this is the case, the cutting speed, horsepower and torque limits for the hobbing machine needs to be re-examined based on the new information available, and adjusted. After adjustment, another gear needs to be cut, and inspected to confirm the changes.

After the final adjustments are made to the cycle, and the tool life is known, the overall cycle is compared to the goals of the desired optimum cycle. Typically, this is a comparison of the new and old cycle times to see if an improvement in productivity was achieved, and a comparison of the new and old tool life. If the resulting tool life is unacceptable for the manufacturing situation, the speeds or feeds may need to be decreased to obtain acceptable tool life. This will negatively effect the improvements in cycle time achieved, but when all the factors are considered, may actually be an overall improvement in productivity.

CHAPTER IV.

TESTING AND CONFIRMATION OF GENERAL METHOD

To confirm the general method developed for the optimization of hobbing cycles on non-CNC machines; it was experimentally applied to Barber Colman 16-15 vertical hobbing machines at the John Deere Waterloo Works. A battery of four of these machines was chosen in Department 428. The confirmation tests were limited to preshave hobbing a family of 5 diametrical pitch helical gears ranging from 21 to 47 teeth. The hobbing tools used to cut these gears were single thread, PM-M3 or M4 hobs with TIN coating. The coolant in these machines was water-based HOCUT 4284B.

Historically, this family of gears was cut using a two pass (rough and finish) cutting cycle. The cycle times for these parts ranged from 6.83 to 12.96 minutes. It was desired to decrease these times and optimize the machining cycles for these parts using the general method developed for non-CNC hobbing machines.

Definition of Optimum Hobbing Cycle for John Deere Waterloo Works

The first step of the general method was to define the desired optimum cutting cycle. At the John Deere Waterloo Works the general definition for the optimum gear hobbing cycle is : "to produce a quality gear as quickly as possible without exceeding the limitations of the machine tool, and with no negative effect on tool life" (K. Magee, personal communication, January 10, 1995). This is based on the high cost of labor and overheads for that facility. These result in high manufacturing costs assigned to the gear for machine cycle time. In this manufacturing situation, any reductions in cycle time can save considerable cost.

Tool life is the second consideration for cycle optimization. When possible, the tool life should be equal to the average order quantity for the gear. If this is not possible, it should be even multiples or divisors of the order quantity. This allows maximum tool life during the run while minimizing the number of tool changes within the run. Tool changes can be very time consuming in the manufacture of quality gears. Lead and profile checks need to be performed after every tool change to assure that the new tool is producing gears to the required specifications. If the results are not to specification, adjustments need to be made before making more gears. During this time, all the machines in the battery are not productive. For this reason tool changes should be kept to a minimum during production runs.

Determination of Optimum Cutting Speed

The second step in the general method was to determine the maximum cutting speed for the machining cycle. This step was a compromise between the limitations of the machine tool and the cutting tool. The Barber Colman 16-15 hobbing machine was originally designed to have a maximum spindle speed of 300 rpm. However, due to age, wear, etc. the machines used to confirm the general method in this study could only achieve a spindle speed of 265 rpm. The TIN coated cutting tool used in this study had a maximum speed of 330 surface feet per minute. For the five inch diameter cutting tool the spindle speed at this surface footage was 245 rpm (using the equations presented in the review of literature). Another consideration for this cutting tool was the small tip radius of the teeth. The tip of the cutting tool does a great deal of work during the hobbing process. It is desirable that the tip have a relatively large tip radius, but this is not always possible because of the geometry of the gear the hob is designed to cut. Hobs are known as "form tools". This means that the desired form of the resulting product is ground into the cutting tool, which transfers this form during the machining process to the resulting part. For this reason, the tip radius of the cutting tool can not be changed. Because of the large width of the gears cut in this study, and the tip radius of cutting tool, a spindle speed of 200 rpm was selected as the desired optimum. This was a compromise between cycle time reduction, and the need to have no negative effect on the current tool life.

Calculation of Maximum Practical Cutting Horsepower

To prevent damage to the machine tool, it was important to determine the maximum cutting horsepower the machine could safely handle. This cutting horsepower becomes the limit for the optimum cutting cycle. The first step in the determination of the maximum cutting horsepower is to determine the original designed motor horsepower for the hobbing machine. In this case, the Barber Colman 16-15 machine was originally equipped with a 15 HP motor.

The next step was to determine the losses in the hobbing machine. This study used the theoretical method outlined in the description of the analytical method. In this method the losses of each of the drive train components of the hobbing machine were calculated. It was originally desired to use the empirical method to confirm the theoretical calculations, however no electricians were available during the course of the study to measure the actual current draw of the motor during the cutting process. A schematic showing the components of the hob drive train was shown in Appendix A. In Appendix C are the calculations used to determine the horsepower losses in the hobbing machine during the machining cycle.

By subtracting the losses from the available horsepower, a maximum cutting horsepower of 6.5 HP was defined as the limit for the machine. This cutting horsepower includes a 10 % factor of safety to prevent operating the motor at the maximum power rating. This factor was included primarily in consideration of the age and condition of the motors currently on these machines.

Determination of Maximum Practical Cutting Torque

To determine the torsional limit for the Barber Colman machines, the experimental procedure outlined in the development of the general method was followed. This involved cutting and inspecting a series of gears at incremental feed rates to determine at what cutting torque the torsional limit of the machine was exceeded. This point was indicated by the appearance of a bow in the lead of the resulting gear.

The series of single pass cuts were made at 200 spindle rpm for representative gears in the study group. From the resulting lead charts, and computer calculations for each of the machine cycles, it was originally determined that these particular machines, cutting this family of gears would produce unacceptable gear leads at approximately 1600 in-lb. of cutting torque. The experimental results are summarized in Appendix D.

For this particular family of gears, to get the cutting torque below 1600 in-lb. required unacceptably small feed rates. At these feed rates the cycle time was much longer than the current two cut cycle time. Based on this, it was determined that a two cut cycle was necessary to remove the bow from the lead and produce a quality gear. The premise for this method is that the gear manufacturer can achieve shorter cycle times with a two cut cycle, compared to a one cut cycle with an extremely slow feed rate, for the same resulting gear quality. The hobbing machine will produce wind-up during the first pass where most of the material is removed. A small amount of stock is left for the second pass, in this case 0.5 mm per tooth flank. The cutting torque required for the second pass is much less than the first pass, which produces a gear with an acceptable lead. The torque on the second pass becomes the limitation rather than the torque on the first pass. For the family of gears in this study, the 1600 in-lb. torsional limit was applied to the second pass, and the 6.5 cutting horsepower limit was applied to the first pass.

Experimental Results

Using the general method developed to optimize machining cycles on non-CNC hobbing machines, the limits developed for the Barber Colman 16-15 hobbing machines cutting 5 diametrical pitch helical gears are shown in Table 1.

Table 1

Limits for Barber Colman 16-15 hobbing machine.

Optimum cutting speed	200 r.p.m.
Maximum practical cutting horsepower	6.5 h.p.
Maximum practical cutting torque	1600 in-lb.

The original cycles for these gears on the Barber Colman machines were two pass, with a spindle speed of 180 rpm and 0.100 inches per revolution feed on the first pass, and 0.150 inches per revolution feed on the second pass. At the beginning of this study, it was desired to cut the gear using a one pass machining cycle. However, during experimentation to determine the torsional stiffness for the machines, it was also determined that the feed rate for the 5 pitch gears in this study would have been unacceptably small for the cutting torque to be below the torsional limit for the machines. These slow feedrates would have increased, rather than decreased, the overall machine cycle times. For this reason a two cut machining cycle was necessary. Applying the cutting horsepower to the first pass, and the torsional limit to the second pass, a machining cycle with a spindle speed of 200 rpm and a first pass feed rate of 0.100 inches per revolution and a second pass feed rate of 0.160 inches per revolutions was developed.

Initially, this cycle appeared to work as predicted by the general method. Tool life was the same, or slightly better than originally. Unfortunately, after running several different lots of material over a period of several weeks, quality problems began to occasionally appear. Upon investigation, it became apparent that some of the machines in the battery had torsional limits less than the 1600 in-lb. determined experimentally on one of the machines. To compensate for the machine to machine variations in the battery, the feed rate for the second pass was revised to 0.150 inches per revolution.

The development of the machining cycles is summarized in Appendix E. Tool life was the same, or slightly better for all the gears in the study group. Cycle times were reduced 10 % to 12 % from the original cycles. This resulted in a cost savings of between \$0.97 to \$2.19 per gear.

CHAPTER V.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary of Analytical Method

This study was to develop a simple, analytical method for the optimization of machining cycles on non-CNC gear hobbing machines. Current tooling technology has advanced beyond the capabilities of gear hobbing machines designed only fifteen years ago. This has created a situation where the determination of machining cycles needs to consider both limitations of the cutting tool and the machine tool. This method filled a need in the gear manufacturing industry to improve productivity on non-CNC equipment and utilize the cutting tools and machines to their full potential. The final method developed consisted of the following five steps:

1) Define the optimum cycle for the given manufacturing situation.
2) Optimize the cutting speed.
3) Maximize the practical cutting horsepower.
4) Maximize the practical cutting torque.
5) Analyze the resulting cycle and approximate tool life.

The general method was developed based on a combination of the limits of the cutting tool and the non-CNC hobbing machine. It considered the strength and cutting speed limitations of the cutting tool, and the spindle speed, rigidity, horsepower and torsional stiffness limitations of the machine tool.

Summary of Test Results

The general analytical method was applied to non-CNC hobbing machines at the John Deere Waterloo Works. It was limited to the Barber Colman 16-15 vertical hobbing machine cutting 5 diametrical pitch helical gears using a single thread M3 or M4 cutting tool in waterbased coolant. The purpose was to experimentally confirm the applicability of the general method in industry.

The testing showed that the general method could be successfully applied to a given make and model of hobbing machine. The specific limits developed for these machines cutting the gears used in this study were: 200 rpm spindle speed, 6.5 cutting horsepower, and 1600 in-lb. of cutting torque. The horsepower limitation was applied to the first pass of the machining process, and the torque limitation was applied to the second pass. The resulting machining cycle met the criteria for the optimization at this facility. Overall, it resulted in a 12 % reduction in cycle times, with the same or slightly better tool life This represented and average savings of $1.60 per gear. (see Appendix E) The tests also showed that the possibility of machine to machine variations exists. During experimentation, variations in the torsional stiffness of different machines were noted. This violates one of the initial assumptions made at the beginning of the study.

Limitations

Experimentation showed that there were several limitations to this general model. The first was the initial assumption that all similar machines behave in a similar manner. This was not the case, as torsional stiffness variations were noted from machine to machine. As a result of this, the specific limits defined for the general method also needs to consider allowances for variation in the condition of different hobbing machines of the same basic model while defining the limits for torsional stiffness.

The second limitation of the general method was failure to identify the special considerations necessary for a two pass machining process. During experimentation it was determined that the cutting horsepower limitation should be applied to the first machining pass, and the cutting torque limitation should be applied to the second machining pass.

Another limitation of this study was the determination of the cutting horsepower limit based only on the theoretical losses in the machine. No maintenance electricians were available during the course of the study to measure the actual power consumption of the machine tool, and determine the losses empirically. This study was limited in the fact that the theoretical values were not confirmed by actual measurement.

A general limitation of the method was that specific limits could only be defined for a narrowly defined process. The hobbing machine, the pitch range, type of gears (helical vs. spur), and the general type of machining (preshave vs. finish hobbed) all needed to be defined to arrive at the limits for optimizing the process. It would be ideal if the general method could define more widely applicable limits. This limitation requires more work on the part of the gear manufacturer who produces a wide variety of gears.

The last limitation of the general method, was that it did not totally eliminate the "cut and try" approach to determining machining cycles for non-CNC hobbing machines. Using the general method the gear manufacturer could be assured that the initial trial was much closer to the optimum, but some experimentation would still be necessary.

Conclusions

In conclusion, a simple analytical method for the optimization of machining cycles on non-CNC hobbing was developed. This method used as criteria a combination of the limitations of the cutting tool and the non-CNC hobbing machine. Specific limits for the cutting speed, cutting horsepower and cutting torque were developed for the manufacturing situation. Part of this situation included a specific model of hobbing machine, the Barber Colman 16-15 machine. Using the general method, limits for other models of hobbing machines could be developed. The same steps would be used; define the optimum for the manufacturing situation, optimize the cutting speed, maximize the practical cutting horsepower, maximize the practical cutting torque, and analyze the resulting cycle. The resulting limits for other machines would be different than those developed for the Barber Colman machines in this study. The limits would also be different for different pitch ranges and sizes of gears. More work is necessary to refine the application of the general method.

Recommendations

Based on the analysis of the test results, the following recommendations are made for further research into refinement of the general analytical method for the optimization of machining cycles on non-CNC hobbing machines. The first recommendation is further research into the power and speed limitations imposed on the cutting cycle by the tip radius of the cutting tool. During confirmation of the analytical method, the cutting speed was limited to 200 rpm based on previous experience with the cutting tool used. This limitation was not outlined or described in the general method. (Note: There was no mention found during the review of literature of the limitations of the cutting tool due to small tip radii).

The second recommendation is for further research into what assumptions were in the computer programs that calculate cutting horsepower and torque. If the assumptions in these equations become better understood, this will assist in refinement of the general method. As the programs used in this study were proprietary in nature, no research into the assumptions in these programs was possible.

Lastly, it is recommended that the theoretical losses in the machine, which were used to determine the cutting horsepower limit, be confirmed by actual measurement of the total power consumed in the machining process. The cutting horsepower limitation should then be revised accordingly to give more accuracy in the application of the general method.

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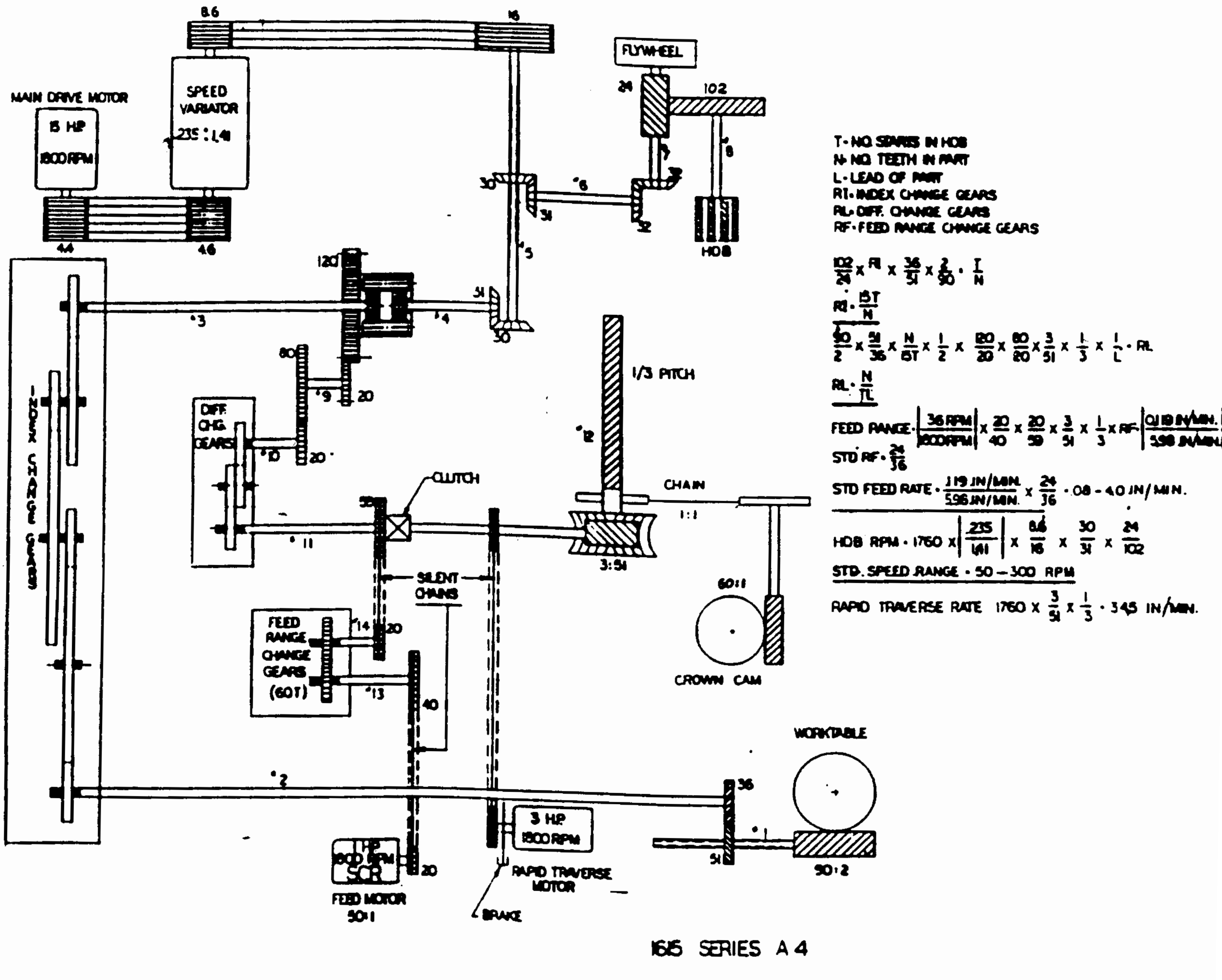
APPENDIX A

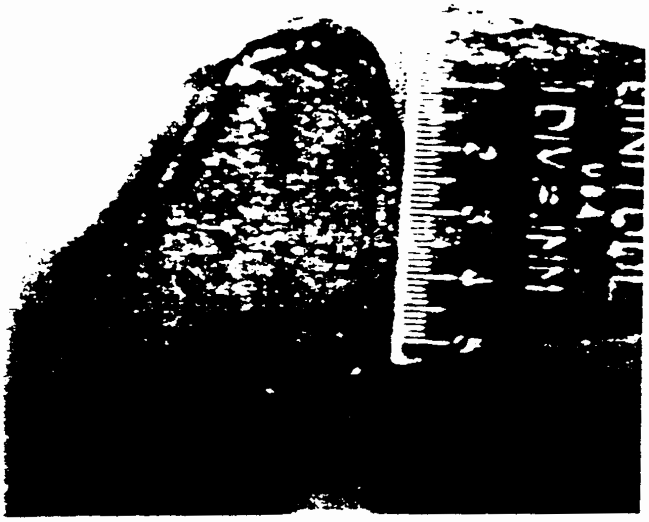
SCHEMATIC OF BARBER COLMAN 16-15



1615 SERIES A 4

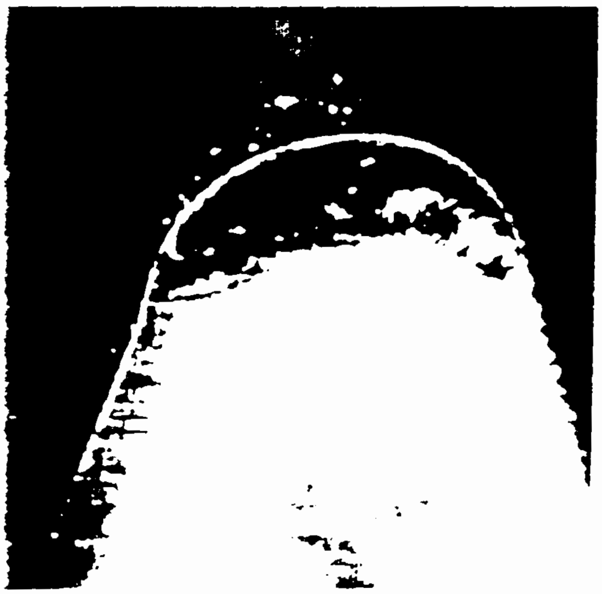
APPENDIX B

ILLUSTRATIONS OF CUTTING TOOL WEAR



Desired Tool Wear

[illegible] Wear



[illegible] Wear

MAXIMUM CUTTING POWER CALCULATIONS FOR BARBER COLMAN 16-15

Date: 12 APR 94

By:

SUBJECT: B.C. – SAFE H.P. CALCULATION

Subs

File No.

☐ Microfilm ☐ Cull

☐ Transfer To:

GEARS % Loss

HOB SPINDLE

2	BEVELS	(.03)	= .06
1	HELICAL	(.02)	= .02
			.08

TABLE* DRIVE

1	BEVEL	(.03)	= .03
4	SPUR (Diff)	(.02)	= .08
4	SPUR	(.02)	= .08
1	HELICAL	(.02)	= .02
1	WORM	(.06)	= .06
			.27

* ASSUME TABLE H.P. IS 1/4 H.P. of CUT

MOTOR H.P. REQUIREMENT

= (HOB H.P + TABLE H.P.) EFF/SAFETY FACTOR

→ ASSUME .5 SAFETY FACTOR – BEARING LOSSES, AGE OF MACHINE, ETC.

= (1.08 CUT H.P + 1.26(.25) CUT H.P.)(1.50)

= 2.09 (HP of CUT)

TO AVOID EXCEEDING MOTOR CAPACITY + ALLOW for BELT LOSSES .9 for MOTOR

WITH MOTOR ALLOWANCE:

→ **MACHINE H.P = 2.32 × H.P. of CUT**

* "DESIGNED" H.P = 15 for Main Drive Motor

MACHINE H.P. NOT TO EXCEED 15

RESTATED: **H.P. of CUT NOT TO EXCEED 6.5**

APPENDIX D

SUMMARY OF EXPERIMENTAL RESULTS

Table H1 summarizes the results of the single pass machining cycles used to determine the torsional limit for the Barber Colman 16-15 hobbing machines cutting 5 diametrical pitch helical gears. The column labeled "Acceptability" simply defines whether the amount of wind-up shown in the lead trace for that gear was acceptable or not for the parts produced.

Table D1.

Incremental Feed Rates at 200 rpm, Single Cut Machining Cycle

Test Number	Feed Rate (ipr)	Calculated Cutting Torque (in-lb.)	Cycle Time (min.)	Wind-up (mm of lead error)	Acceptability (Yes or No)
# 1	0.08	1911	9.61	0.030	No
# 2	0.075	1813	10.26	0.030	No
# 3	0.070	1721	10.93	0.020	No
# 4	0.065	1659	11.44	0.010	No (borderline)
# 5	0.060	1500	12.94	0.004	Yes

Figure D1. Test # 1 Lead Trace: 0.030 mm Lead Error

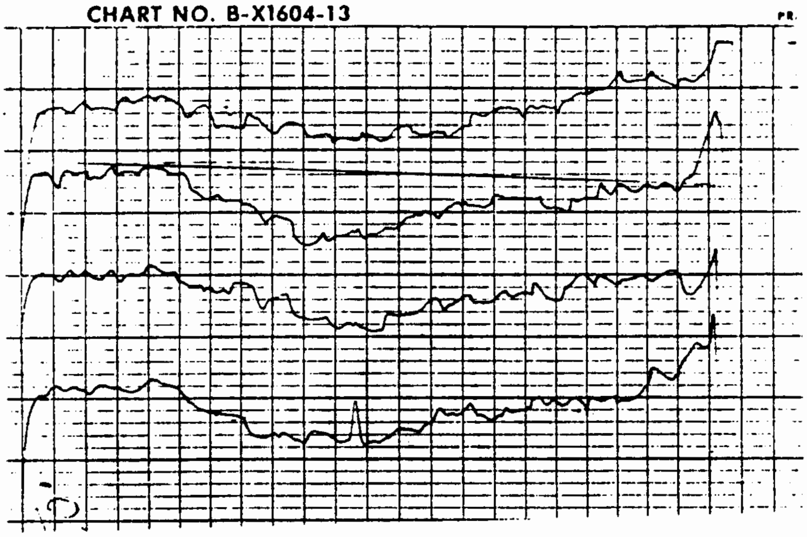


Figure D2. Test # 2 Lead Trace: 0.030 mm Lead Error

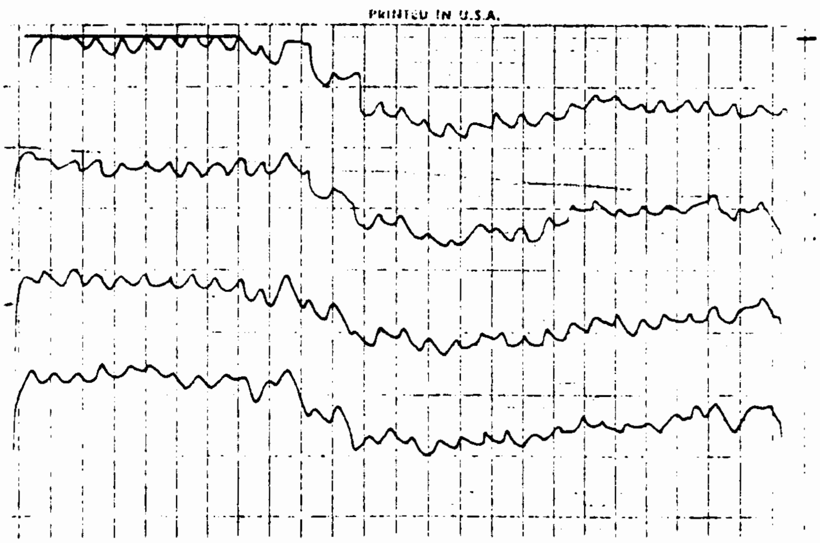


Figure D3. Test #3 Lead Trace: 0.020 mm Lead Error

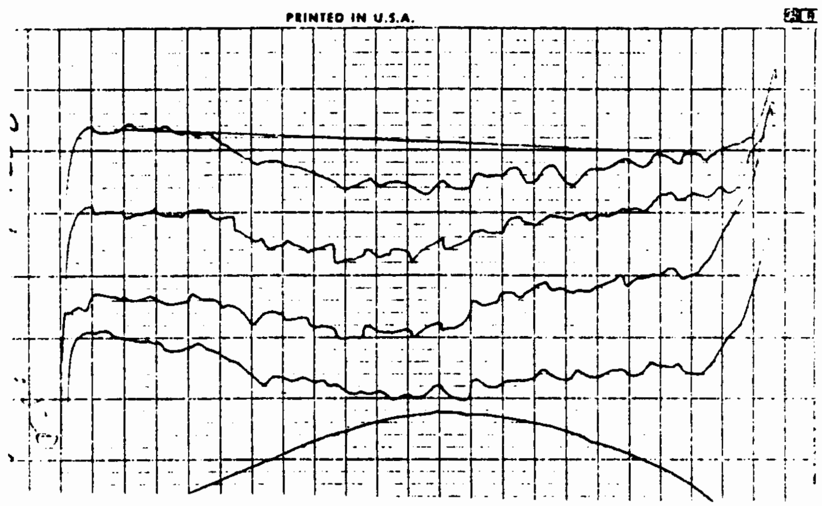


Figure D4. Test # 4 Lead Trace: 0.010 mm Lead Error

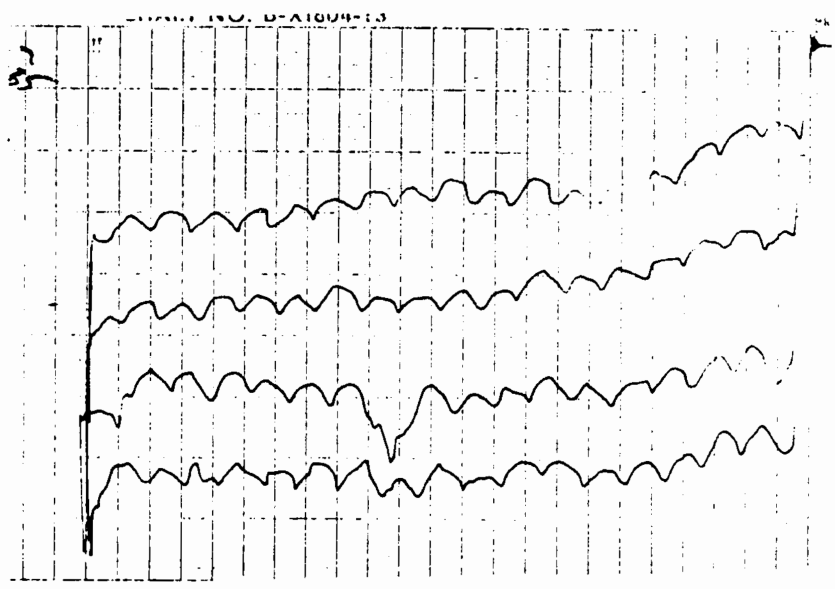
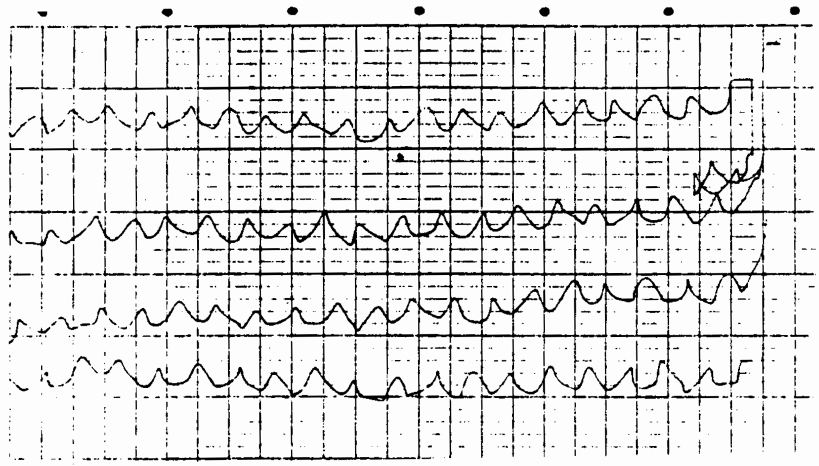


Figure D5. Test # 5 Lead Trace: 0.004 mm Lead Error



APPENDIX E

SUMMARY OF DEVELOPED MACHINING CYCLES

Cycle Optimization - Summary of Experimental Results

23-Apr-95

Part #	Machine	Machining Cycle Parameters 1st cut	2nd cut	Shft (in.)	Tool Life	Teeth	Cycle Time (min)	Comments	Reduction (min)	Percent	Est. Savings ($ per piece)
R83755	1682	180 x .100	180 x .150	0.040	83	21	6.83	Orginal			
	1683	200 x .100	200 x .150	0.040	83		6.17	New/Improved	0.66	10%	$0.97
	1663	200 x .100	200 x .160	0.040	83		6.06	not consistant machine to machine			
	1883	200 x .080		0.040	83		5.26	Wind-up in Lead			
R83619	1795	180 x .100	180 x .150	0.048	69	24	9.16	Orginal			
	1683	200 x .100	200 x .150	0.045	77		8.15	New/Improved	1.01	11%	$1.19
	1663	200 x .100	200 x .160	0.045	77		7.99	not consistant machine to machine			
	1683	200 x .080		0.045	77		6.76	Wind-up in Lead			
R94163	1795	180 x .100	180 x .150	0.048	72	24	10.02	Orginal			
	1663	200 x .100	200 x .150	0.045	77		8.91	New/Improved	1.11	11%	$1.22
	1663	200 x .100	200 x .160	0.045	77		8.74	not consistant machine to machine			
	1663	200 x .080		0.045	77		7.33	Wind-up in Lead			
R84163	1795	180 x .100	180 x .150	0.048	68	27	10.25	Orginal			
	1663	200 x .100	200 x .150	0.050	66		9.06	New/Improved	1.19	12%	$1.41
	1863	200 x .100	200 x .160	0.050	66		8.89	not consistant machine to machine			
	1663	200 x .080		0.050	66		7.62	Wind-up in Lead			
R84165	1795	180 x .100	180 x .150	0.048	77	31	10.99	Orginal			
	1663	200 x .100	200 x .150	0.050	74		9.63	New/Improved	1.36	12%	$1.91
	1883	200 x .100	200 x .160	0.050	74		9.45	not consistant machine to machine			
	1683	200 x .080		0.050	74		8.16	Wind-up in Lead			
R83614	1795	180 x .100	180 x .150	0.048	66	34	12.96	Orginal			
	1663	200 x .100	200 x .150	0.050	66		11.41	New/Improved	1.55	12%	$1.96
	1663	200 x .100	200 x .160	0.050	66		11.19	not consistant machine to machine			
	1663	200 x .080		0.050	66		9.64	Wind-up in Lead			
R94188	1795	180 x .100	180 x .150	0.048	66	34	12.96	Orginal			
	1682	200 x .100	200 x .150	0.050	66		11.41	New/Improved	1.55	12%	$2.19
	1882	200 x .100	200 x .160	0.050	66		11.19	not consistant machine to machine			
	1662	200 x .080		0.050	66		9.64	Wind-up in Lead			
R84164	1795	180 x .100	180 x .150	0.110	31	36	12.01	Orginal			
	1662	200 x .100	200 x .150	0.045	74		10.72	New/Improved	1.49	12%	$1.95
	1662	200 x .100	200 x .160	0.045	74		10.52	not consistant machine to machine			
	1662	200 x .080		0.045	74		9.17	Wind-up in Lead			
									Average:	12%	$1.60