A Review of New Strategies for Gear Production

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Abstract

The traditional gear machining methods such as hobbing and shaping pose limitations on manufacturer’s ability to efficiently manufacture gears in small and medium batches. In recent years, two new gear machining methods (InvoMilling\textsuperscript{1} and five axis machining using gearMILL) have been developed that allow use of standard multi tasking machines and standard tools to provide a solution to these limitations. This paper describes the two techniques and compares their quality and production times with those of traditional gear manufacturing techniques. The paper discusses additional benefits of the two new methods in enabling new gear design strategies and efficient machining of special gear forms. In conclusion, it was found that the new methods are capable of providing better quality gears than the traditional methods in preheat operations. While there is no single method which gives the best cycle time for all gears, multi-tasking machines provide the flexibility to use the method that best satisfies customer needs.

Keywords: Spur Gear; Helical Gear; Bevel Gear; Hobbing; Shaping; Milling; Gashing; InvoMilling

1. Introduction

The strategies historically utilized for machining the teeth of gears have relied on specialized machine tools and cutting tools. The quality levels and production times associated with these solutions were generally acceptable, but other elements of the commercial situation were not. Specifically, the lack of agility to redeploy the machines for various gear types, the long lead times required to acquire tools and machines, and the high cost of the equipment made it impossible for gear producers to implement business plans based on agility in terms of rapid response to customer demands or transition from production of one type of gear to another. Recently developed alternatives utilize standard machines and standard cutting tools to cut the gear teeth. The two solutions which have been particularly effective in enabling machining centers to productively cut gears are InvoMilling, \cite{InvoMilling} \footnote{InvoMilling is a registered trademark of Sandvik Coromant Inc.} a gear cutting strategy and tooling developed by Sandvik, and gearMILL, a software solution developed by DMG Mori Pfronten.

InvoMilling utilizes a face cutting tool to interpolate the involute of the gear tooth. The contact between the plane of the tool face and the tooth’s involute is described by a line, or chord bisecting the plane of the tools face. The tool path is radial, typically from the tip to the root. Therefore the major variables of the gear (module, pressure angle, and helix angle) are determined by the tool path, not the tool itself, a characteristic generally associated with flank or ball end-milling rather than hobbing, gashing, or shaping tools. Unlike end-mills which cut a scallop into the work with each pass,
there is no correlation between stepover distance and surface texture for the InvoMill’s chord of contact. This enables large step-overs of typically 5 to 15mm for the most common gears in the range of module 3 to 6. In comparison an end-mill would be limited to step-overs of .1 to .3mm. As a result the productivity of InvoMilling can be one to two orders of magnitude greater than end-mill cutting of a tooth.

![Fig. 1 InvoMilling Process](image1)

However the InvoMill shares a constraint with the end-mills which is difficulty in preparation of a tool path for the CNC program. The traditional CAM solutions are ineffective as the solid models of gear profiles on which they are dependent are generally unavailable. There are multiple reasons; one is that many legacy gear designs predate solid modeling so only drawings and gear parameters are available, and another is the deficiencies in the solid models when they are available. Because programming systems for traditional gear generation equipment utilized the parameters of a gear and did not require a solid model, there has been little justification for the effort to accurately model the complexity of the gear tooth, with its subtle complications such as crowning, tip clearance, and root modifications. The gear designers knew that their solid models would not be used for manufacturing and did not push the CAD providers to develop effective modeling tools. This problem was solved by development of surface based gear solid model generating software gearMILL. This enables programming of gears which lack models, and those which are imperfectly modeled.

This paper focuses on the impact of these two solutions, in terms of productivity, quality, business strategies, and enabling new gear design strategies.

2. Productivity

InvoMilling process and hobbing process are comparable processes because both are primarily used for machining of cylindrical gears. For comparison of cycle times using the two methods, machining times for module 3 and module 6 gears are calculated. The cycle times for high-speed steel hobbing were derived according to industry standard feeds and speeds, recommendations taken from Gear Hobbing, Shaping and Shaving [2]. The cutting parameters used for both hobbing and InvoMilling are shown below in Table 1. The cutting parameters for both hobbing and InvoMilling are considered conservative cutting conditions.

![Fig. 2 Module 3 cycle time comparisons](image2)

| Table 1 | (a) hob cutting parameters (b) InvoMILL cutting parameters.
<table>
<thead>
<tr>
<th>Module</th>
<th>Hob Dia mm</th>
<th>Feed per rev mm</th>
<th>Cutting Speed m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8.25</td>
<td>2.54</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>114.3</td>
<td>1.52</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>Hob Dia mm</th>
<th>Feed deg per rev mm</th>
<th>Cutting Speed m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>80</td>
<td>1000</td>
<td>244</td>
</tr>
<tr>
<td>6</td>
<td>135</td>
<td>1000</td>
<td>244</td>
</tr>
</tbody>
</table>

The InvoMilling cycle time calculations were derived using Manufacturing Suite, a virtual machine simulation software. The cycle times in Figure 3 compare high speed steel hob double cutting to InvoMilling for module 6 spur gears.

![Fig. 3 Module 6 cycle time comparisons](image3)
Equation 1 was used for hobbing cycle time evaluations.

\[
T = \frac{Z \times L}{N \times K \times F}
\]  

(1)

Where:  
- \(T\) = cycle time in minutes  
- \(Z\) = number of gear teeth  
- \(L\) = Length of cut in millimeters  
- \(N\) = hob revolutions per minute  
- \(K\) = number of hob starts  
- \(F\) = feedrate in millimeters per minute

As seen in Figures 2 and 3 above, as the face width of the gear decreases, the productivity gap between hobbing and InvoMilling decreases. This is because of the inherent infed and overshoot distance always needed when hobbing. InvoMilling productivity also increases as the size of the tooth increases. As seen in Figure 3, InvoMilling becomes more productive than double cut hobbing for module six gears. The same trend will continue for module sizes larger than six and for some module sizes below six.

Table 2. Process capability of different gear manufacturing processes[3]

<table>
<thead>
<tr>
<th>DIN</th>
<th>AGMA 2000 Quality Level</th>
<th>Grind</th>
<th>Hard Finish</th>
<th>5 Axis (SHAPE/RACK)</th>
<th>Shape/Disc</th>
<th>InvoMilling</th>
<th>Hob A</th>
<th>Hob B</th>
<th>CBN Form Finish</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>X</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td></td>
<td>X</td>
<td>X</td>
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<td></td>
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<tr>
<td>4</td>
<td>12</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<td>6</td>
<td>10</td>
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<td></td>
<td>X</td>
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<td>7</td>
<td>8</td>
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</table>

X – Max achievable quality by the method

The above analysis shows that no single gear manufacturing method is best for machining every gear. Multi-Tasking machines offer the flexibility of hobbing small module parts and InvoMilling large module parts. Hence users can optimize their manufacturing process.

Additionally in the analysis above, only the cycle time is considered. If total time is considered – which consists of setup time and machining time, traditional methods have significant limitation due to higher setup times. For small and medium batch production, the setup time becomes relevant. Then InvoMilling will be able to outperform hobbing due to its lower setup time and hence lower overall time.

3. Quality

Manufacturing processes used to produce gears have certain capability limitations when it comes to quality achievable. Some of the variables that change the gear quality achieved are the machine, cutting process, work fixture, cutter, arbor, machined blanks, and cutting parameters. Because multi tasking machines can apply multiple cutting processes and use various tools, the user has flexibility to choose the cutting process based on quality and productivity requirements.

Inspection of a gear cut by the InvoMilling process is shown in Figure 4. The quality achieved is A2000-A88 Q13. As seen from Table 2 and Figure 4, overall InvoMilling produces a better quality gear than hobbing.

4. Gear Design Strategies

Gear root is a very important part of the gear of the gear. The stress concentration point typically lies in the tooth to root transition area and this is typically the point of failure [4]. Gear manufacturing using generation has limitations when it comes to the root area. The root area is generated by the tip of the hob. The involute and root form depends on the hob tip radius, number of teeth and the profile shift coefficient (x). Once a hob is manufactured, the hob tip radius is fixed. A hob can manufacture gears of a single module and varying number of teeth and the tooth root radius produced by the same hob will be different for different number of teeth. A gear with smaller teeth runs the risk of having undercut at the root while
a gear with a larger number of teeth will have a sharper radius at the root (Fig. 5). When the number of teeth increases, the gear form approaches the form of the basic rack of the hob.

Lesser bending stresses in the root are very important. Reduced bending stress implies that a specific gear will be able to carry higher load. This may allow the specification of a reduced module. If designers can use a lower module gear instead of a larger one, it would mean higher transfer efficiency, reduced noise and vibration and cost savings. If the designers keep the module of the gear the same but reduce the bending stresses, it would mean longer lifetime and higher factor of safety. Considering the widespread application of gears for motion and power transfer, the increased efficiency would amount to significant energy and cost savings[5].

New manufacturing methods such as InvoMilling or 5 Axis Machining allow the user a better control over the root geometries because it uses different tools for machining of the root area and Involute gear form (Fig.6). Hence the best geometry for the root can be designed irrespective of other constraints such as number of teeth and profile shift. The new manufacturing methods can also speed up the whole product development process because prototyping is very fast and hence many designs can be quickly tested.

The methods are easy to use and adhere to standards. The tools are typically stocked-standards enabling a reduction in the cost of consumable tooling per gear. The tooling used with these methods is solid carbide or inserted carbide tooling. This type of tooling has predictable tool wear which can be controlled. Hence it is possible to get better part to part variation in the manufacturing process.

Overall the designers now have much better freedom to choose the root profile that gives them a stronger gear because they can machine these root forms efficiently using new manufacturing methods.

5. Manufacturing of special gear forms

Currently there are various forms of gears that are being manufactured. Involute form is one of the most common form. Convoloid form, and special herringbone forms are some other spur and helical gear forms. On the bevel gear side, the Gleason type, Klinglenberg type, Formate and other forms are used. Designers have researched special forms and explained their benefits [6]. One of the reasons, Use of special forms have been limited is lack of productive and efficient manufacturing processes. In many cases special machines need to be designed to cut special forms and hence manufacturing of these tooth forms was a challenge. Additionally, these forms will continue to evolve and there will be many more forms designed in future.

Multi-tasking machines are very flexible. If a parametric model or a CAD model can be defined for the form, the form can be machined using these machines. While it cannot be said with certainty, but Multi-tasking machines offer the best possibility for a customer to be able to make not only today’s gear forms but also the ones that will be designed in the future. As an example, the gears shown in the Fig. 7 are special forms of gears that are equivalent to herringbone gears. These gears offer significantly better capability to absorb shock and offer excellent application for locomotives. The adaptability of these gears can increase (in turn increasing the overall efficiency of transportation) if they can be manufactured efficiently. Multi-tasking machines will reduce one of the hurdles in doing that. If the customer/designer can define the forms mathematically and has a solid model, these forms can be efficiently manufactured.
6. Summary

It is obvious that 5-axis and turn-mill CNC machines can support a wider range of gear cutting solutions than dedicated and single-purpose gear cutting machines. This agility is attractive for various business models and it does not need compromises in quality and productivity. In fact we have observed that in some cases the agile machines offer even higher productivity, and higher quality levels. As a result the selection of capital equipment for gear production must be based on thorough investigation of application-specific solutions if agility is to be pursued without compromise in productivity or quality.

7. Future Research

Additional research will be required to characterize the influence of the unique surface texture created by InvoMilling. The InvoMill produces a surface more like a ground surface than like a hobbed surface. It is possible that the smooth finish will generate less noise, but may not hold lubrication as effectively as the dimpled hobbed surface which could result in reduced fatigue life. There is considerable research correlating the fatigue life of gears to their surface texture, both by life testing and by simulation [7, 8]. It would be advisable to confirm or refute these speculations with testing of noise and fatigue, and simulation to predict what the ideal surfaces might be, and then try to replicate them.

References

[1] Scherbarth S., Tooth Cutter and method for cutting the teeth of gear tooth elements, patent application DE102010042835A1