Economics of Machining Bevel Gears on Multi Tasking Machines

Historically, there were two main ways to make a bevel gear. In the past five years, things have changed significantly.

By Nitin Chaphalkar
Bevel gears have been made for over 50 years. There have been several incremental improvements to the initial methods, but the fundamental principles of machining these gears remain the same. Historically, there were two main ways to make a bevel gear.

One method used specialized equipment and tooling; the other one used very simple tools (endmills) and required a solid model of the gear. It was a compromise either way. For the first method, customers had to wait for the right tooling to arrive and/or have special skills to prepare/modify the tooling. For the solid model-based method, the solid models were never right or complete enough to get good surfaces and contact patterns, and the productivity of the process was lower. Additionally, the two methods required completely different machines, operator skillsets, and programming software.

In last five to six years, things have changed significantly. Development of multi-tasking machines and new programming software combined with the newly-developed machining processes have created an opportunity to give a new glamour to gear machining and usher in 21st century advances. In short, gear manufacturing is reinventing itself.

This article focuses on how these advances are enabling new business plans for customers and on the indirect effects of these technologies.

To explain what I mean by the “indirect effects” of a technology, let’s take the example of a cell phone. People started using cell phones because they could call from anywhere—they no longer had to be in the office or carry the change for payphone. Parents then gave their children cellphones because that was safer. Improving safety became an indirect benefit of having cellphones. This was not the original motive, but a nice and important indirect benefit nonetheless. Similarly, the multi-tasking machines combined with new processes give several indirect benefits as outlined in the article.

**Bevel Gear Machining Using Multi-Tasking Machines**

Multi-tasking machines are machines with milling and turning capability, a sort of lathe and milling machine combined into one. They could be considered as two main types: Turn-Mill and Mill-Turn. Turn-Mill machines are typically suitable for longer parts (e.g. pinions) while Mill-Turn machines are suitable for larger diameter parts (e.g. gears). These are 5-axis machines that can do many manufacturing processes, machine all sides of the parts, and, in many cases, machine a part to completion. DMG/Mori Seiki already has machines of both these types in their broad portfolio. These machines are used in wide variety of industries including aerospace, medical, industrial, tooling, and now gear manufacturing.

For these new manufacturing processes, the tools are simple (end mills or disc cutters) with no special geometry for any specific gear form or tooth. No special option is required on the machines to make them produce gears. The key here is to generate the toolpath and create the gear geometry. This is where the programming software is so vital to the process. The programming software gearMILL effectively handles the complexity of bevel gear geometries by making it visual. It does not need a solid model, and will create a surface using analytical data provided in gear data sheets. This way, customers can continue to use the gear design software that they currently use.

The software can currently program cylindrical gears, bevel gears, and worm wheels. It primarily uses two types of processes—one with flank milling (5-axis machining) and other using disc cutters (InvoMillingR). This means that same gear can be programmed in two different ways, using two different methods, while using the same machine and gear input data.

The software not only defines the geometry of the gear tooth but can also program the contact patterns. Under conventional processes, adjustment of this contact pattern
is a skillful task—one has to do it either by lapping or by modification of the tool. The software makes it visual and easy to adjust. It makes the contact pattern adjustment more of a science than an art.

QUALITY OF THE GEAR MACHINED

The quality of the gears produced by these methods is very good. Quality, as always, is proportional to cycle time. The more cycle time that one can spend the better the quality one can get. By definition, the above processes are milling processes. Hence, the quality of the gear tooth depends on milling process characteristics—stepover and feed rate. The stepover will affect the profile of the gear while the feedrate will affect the lead. Profile and lead errors on the tooth form will be shown on the quality charts from CMM measurement data. The methods allow machining of pre-heat treated and post-heat treated parts on the same machines.
**SHOW ME THE MONEY! ECONOMICS OF BEVEL GEARS**

All of the commentaries about “how well you can do the gears” or “how fast/slow you can produce them” or “how easy it is to program” are necessary prerequisites to consider, but not sufficient conditions to use these processes. But the case falls apart if the economics of the process do not justify. Readers of this article are very familiar with traditional bevel gear machining process costs (tooling costs, total times for machining, etc.). So here is an idea of what a cost-per-part would be for a part machined using multi-tasking machines.

I would first like to explain the key economic differentiators between the two processes. These are the “indirect” benefits that I explained earlier. Direct benefits are, of course, the ability to use standard tools, and the ability to program and adjust the parts just as needed. Now to the indirect benefits.

**LEAN MANUFACTURING**

Reduced work-in-process, minimal idle resources (tools, machines, labor, etc.), reducing points of failures (single-point of failure is the best), and eliminating bottlenecks are all important aspects of lean manufacturing. By combining operations and including gear milling operations in the same setup as turning + milling, a leaner manufacturing process can be achieved.

Turning machine + milling machine + hobbing machine, as a sequential operation, will need a larger workforce and significantly more floor space. The need for buffers at each of these machines means significant work-in-process. Combining all operations into one machine with only one operator reduces work-in-process inventory. Additionally, this machine is the single point of failure—which is ideal. If any of the turning, milling, or hobbing machines go down, the whole line is affected. This is measured as production efficiency.

Let us assume that uptime for each machine is 90%. In the sequential operations, if any one machine fails, the whole machining cell is shutdown/operates at lower efficiency. Hence, the net uptime of such a cell is 0.9 x 0.9 x 0.9 = 0.729 or 73%. A multi-tasking machine performing all operations and producing a part complete will have an uptime of 90%. Machining the part in a single setup has many other advantages. For example, the concentricity between gear pitch circle diameter and OD/ID of the gear is inherently ensured and that will improve the noise quality of the bevel gear.

**COST OF CARRYING TOOLING INVENTORY**

Traditional methods use specialized tooling where the gear form is built in the tool profile. Customers need to maintain a large inventory of hobs and bevel gear tooling (depending on the variety of parts they machine), because they don’t know what they will need to machine next. This large inventory of tools really adds to the “tied-up capital” necessary for running the business. For example, if you have a $1 million-cost of tools in your inventory, though you are just keeping them there without using much, it is equivalent of having a $1 million-dollar machine sitting idle without doing anything—and you will still need to pay interest on it. At 10% cost of capital (conservative estimate) this is equivalent of having $13,215/month carrying cost. For one shift operation (12 hours) 20 days in a month, this accounts for 55$/hr. The individual inventory cost and
cost of capital may be different, but this is a number that cannot be ignored. (Please note that this does not include the cost of ordering new tooling or regrinding the tooling, which is about 2.7% of the total operating cost for an average job shop ($16-million revenue) which accounts for about $450,000. These are costs incurred only when machining the parts and depend on how many parts are actually machined.)

Sometimes it may be justifiable to carry this large tooling inventory, e.g. a large-volume manufacturing plant that makes just a few types of parts and uses carbide tooling. Additionally, the individual inventory value and cost of capital may be different—but again, the bottom line cannot be ignored.

**TOTAL TIME OF PROCESSING**

When comparing two processes, it is common practice to compare their cycle times. However, what really matters is the total processing time. This includes setup time and cycle time. Setup time is not just the time to setup a job—it’s the
actual time required to get a first good part. The smaller the batch size, the larger the influence of setup time on the overall time. Practices like overruns are common ways to increase the batch size to reduce the impact of setup time. These increase the capital tied up in the inventory. As each part is different, and the context in which it was made is different, it is very difficult to compare the two processes and determine which is the best. However, I would encourage the readers to compare the total cycle times when you compare two processes.

**AUTOMATION**

Multi-tasking machines have multiple options for process automation. Barfeeders and vacuum extractors are all standard options. It is not too foreign to imagine a machining cell making bevel gear parts with a single machine, without an operator. The machine feeds a bar, the main spindle machines the part, and machines the bevel gear. The part is then cutoff and transferred to the 2nd spindle, the back end of the part is finished, and then the part is vacuum extracted out or dropped out into the parts catcher bucket. The machining process uses carbide inserts and can be stable. The machine will automatically select “the next tool” in the tool group (a set of similar tools in tool magazine) when the life of one tool expires. This machine can be remote monitored, and the only thing operator is required to fill up the barfeeder and collect the machined parts from parts bin. There is no robot, no sequential stack of tolerances, no machine sitting idle because another machine is down. It is a very lean operation. It is always possible to add a robot to the machining cell, but there are many things that can be done even without it.

**COST CALCULATIONS FOR “PER HOUR COST OF OWNING THE MACHINE”**

Many readers will be running their production facilities on a per-hour cost basis, which is what we would like to use to essentially define the shop rate of a machine cutting gears on a multi-tasking machine. While isolating a machine to calculate the cost of electricity and cost of leasing the facility (per machine) is slightly difficult, this exercise can quickly yield the cost of owning and operating the machine. Interestingly enough, the tooling costs in this process are only incurred if you are actually machining the part (there is little or no cost of carrying tooling when you are not making any parts. It’s the same case with electricity). The labor cost of $50/hour, at 8 hour/day, 20 days/month and 12 months equals $96K. This includes salary & benefits and is a conservative estimate. Now compare this $101/hour cost to the $55/hour tooling carrying cost. Numbers tell the story themselves. One can clearly see the importance of considering these “indirect benefits”. Truly, the numbers will be different on a case-by-case basis, but I believe the range will be the same.

**SUMMARY AND CONCLUSION**

Overall, it is beneficial to make bevel gears on multi-tasking machines. While many debate about what is the best way to make a bevel gear on multi-tasking machines, my opinion is that no one process is best. Every single process has its benefits, challenges, and limitations. Multi-tasking machines offer a choice of the process that lets customers select the process. This optimizes the whole gear-making operation and increases profits. Finally, while considering these machines as gear-making machines, one should not forget that these are very good milling + turning + 5 axis machines in the first place—so you will have less opportunity to turn down a customer request for machining a part.

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