Chapter 3. Geometric Simulation and NC Verification

Virtual Machining and the Manufacturing Model

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Abstract: This paper discusses the methods and benefits of the modern electronic manufacturing model. Computer software is used to accurately simulate the material removal process of an NC tool path, creating a solid model which accurately represents the "as-machined" part. This model provides manufacturing engineers with a tool to speed and improve the entire NC manufacturing process.

1. INTRODUCTION

Today's manufacturing marketplace is more competitive than ever. The good news is that there are practical, affordable tools and techniques to reduce costs, speed time to market, and improve product quality.

Modern NC simulation and verification software gives engineers the ability to take the guesswork out of NC machining and eliminate costly mistakes and delays through the creation of an electronic "manufacturing model." The manufacturing model is not merely temporary manufacturing geometry used for cursory inspection purposes. Rather, it is a three-dimensional solid created by a computer simulation of the manufacturing process. This "as-machined" manufacturing model is identical to what is anticipated from the final machined product.

The modern manufacturing model provides many benefits. Simulating the NC machining process to create the model verifies that the machining process will go smoothly by reducing or eliminating delays, scrapped parts, broken tooling, and costly machine crashes. Once the model is finished, it can be compared with the design model and inspection models to test the accuracy of the NC tool path program, the NC machine, and different process strategies. The manufacturing model is a valuable reverse engineering tool and a method for engineers to bring the "as machined" part data back into the CAD system. Finally, once its accuracy has been verified, the manufacturing model can also be used to automatically optimize NC program feed rates in order to reduce the required amount of machining time. This boosts productivity, reduces machine wear, prolongs tool life, improves part quality, and decreases time-to-market.

2. CREATING THE MANUFACTURING MODEL – SIMULATING THE NC TOOL PATH

NC verification software provides an "electronic preview" of the NC machining process. The user creates the starting stock material either by specifying the dimensions of some simple shapes, or importing a previously created stock model from a CAD system. Clamps

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and fixtures are defined the same way. The cutters to be used in the machining operation are also set up in the software or imported from a CAD system and stored in the software's tool library. Last, the tool path to be simulated is brought into the program.

With these three pieces of information, the simulation and verification software cuts a three-dimensional solid part, just as a machine tool on the shop floor would. Errors (fast feed contact, gouges, collisions between clamps/fixtures, excess material, etc.) that could potentially ruin the part, damage the fixture, break the cutting tool, crash the machine, or otherwise delay the production schedule are detected prior to sending the NC program out to the shop floor. Most quality NC verification software packages work with G-codes and CAM output to support two-axis through multi-axis milling, drilling, turning, mill/turn, and wire EDM operations, consolidated in a single simulation system.

3. ACCURATE SIMULATION OF NURBS CUTTER PATHS

In order to get the full benefit of the manufacturing model, it is important that the NC simulation and verification program accurately simulates what actually occurs on the machine tool. Because of the complex shapes, NURBS (non-uniform rational B-spline) is an increasingly important method for defining curves in sculptured surface machining. Control manufacturers such as Fanuc, Siemens and Toshiba have developed NURBS interpolation capabilities. And several major CAM developers are following suit.

Until recently, the only way to machine curved surfaces (other than circular interpolation records) was "tesselation" – the process of breaking each curve into a number of short straight line segments, or facets, which the control could understand. But a series of facets to approximate a curve is not smooth, fast, or efficient. Each curve requires many lines of code to approximate the contoured surface, increasing the size of the NC program and machining time. And the facets must remain small, limiting the achievable feed rate.

This changed with the advent of NURBS. NURBS is a mathematical method that can be used for defining a complex curve. This improved shape definition enables machines to cut complex shapes in smooth, continuous motions rather than approximating the shape with a number of short linear cuts. Each curve contains 'control points' and 'knots' which are applied to a formula to express complex shapes in a continuous curve. Because NURBS do not require several discrete motions to create curved shapes, the result is smoother machine motion and higher quality surface finish on parts.

By supporting NURBS curves for tool path simulation, NC verification software enables manufacturing engineers to accurately simulate exactly what takes place on the NC machine tool and create a more accurate manufacturing model.

Of particular importance to those machining sculptured surfaces, are some of the problems NURBS pose for efficient machining. Although they produce smoother motion, each NURBS command travels over a much longer distance than point-to-point motion. While moving along a NURBS curve, the cutter is likely to encounter different material conditions that require different feed rates. A single "safe" programmed feed rate for each NURBS command can be very inefficient or cause incorrect cutting during the NURBS motion.

The problem, however, can be solved with NC verification software that optimizes programmed feed rates (see Section 6 *Reducing Cycle Time – Using the Manufacturing Model to Optimize Feed Rates*). Using VERICUT optimization with NURBS interpolation combines the benefits of NURBS interpolation with a high level of feed rate control. By inserting optimized feed rate values within the NURBS interpolation definition, the feed rate is optimized without changing the trajectory of the NURBS curve itself.

4. USING THE MANUFACTURING MODEL – VERIFICATION, INSPECTION, AND ANALYSIS

Once an accurate representation of the real machining process has been created, the resulting manufacturing model can be used to verify the integrity of the tool path, the accuracy of the machine, and the quality of the machining process.

Often, from the time a part is designed to when it is ready to be machined, the design has passed through several people, departments, companies, and CAD/CAM systems. In the end, it is difficult to tell if the tool path accurately reflects the original design intent. Without a "virtual model," the only way to be sure is to cut the part and do a time-consuming first article inspection.

The manufacturing model provides engineers with an excellent low cost electronic documentation and analysis tool. The simulated cut model can be quickly zoomed, reversed, rotated and viewed as a translucent. The model can be sliced into multiple cross-sections, enabling them to check areas that would be impossible to see on the "real part" – such as the intersection of drilled holes. And, three-dimensional measurements (thickness, volume, depth, gaps, distances, angles, hole diameters, corner radii, and fillet radii, etc.) can be taken of the manufacturing model to verify the dimensional accuracy of the finished part before the tool path program ever leaves the computer.

Using the manufacturing model, anyone involved in the production process can identify an incorrectly machined area or mistake in the tool path by electronically comparing it against the original CAD design model.

The manufacturing model can also be used to test the accuracy of NC machines and machining strategies. VERICUT®, CGTech's NC verification software program, was used at a major U.S. automotive manufacturer to evaluate high speed machining centers. A manufacturing model was created by running a complex die surface tool path through VERICUT. The part was then cut on several different high-speed machines. Each part was inspected on a CMM machine, creating a "cloud" of points which accurately represented the machined surface. The resulting inspection data was compared to the manufacturing model to check how well each machine and machining strategy matched original tool path. This company used the results to compensate for accuracy problems resulting from cutting technique or machine characteristics or limitations.

5. REVERSE ENGINEERING – BRINGING CAD AND CAM TOGETHER

The manufacturing model gives engineers a way to work with NC tool path data in a CAD system. By simulating the material removal process of the NC tool path and exporting useful CAD data, the results of the simulation can be imported into the CAD program. It can then be used for general analysis, or to check if mating parts match correctly in an assembly, for example.

The manufacturing model can also be used to represent the in-process material for subsequent operations. Often, several different machining operations must be performed to create a single part. It is difficult to view the changes to the workpiece throughout these different operations. The manufacturing model is an excellent tool for engineers to be able to visualize these changes. At the end of each machining operation, a new model can be created, exported, and used as the starting stock for the next operation. This not only helps track the progress through the project, but is helpful in avoiding set-up mistakes and machining errors.

6. REDUCING CYCLE TIME – USING THE MANUFACTURING MODEL TO OPTIMIZE FEED RATES

After determining an NC program is error free and produces a dimensionally accurate manufacturing model that matches the original design intent, it is ready for the final step in NC verification – feed rate optimization. Feed rate optimization is the process of analyzing current machining conditions and replacing the existing programmed feed rate with a feed rate that better suits those conditions.

With current technological advances in cutting tools, tool materials, and automatic tool path generation software, it is increasingly critical to use the right feed rate for each and every cut in the NC tool path. By optimizing NC feed rates, manufacturers can significantly reduce the time require to machine parts. Other machining benefits include improved surface finish, reduced machine & cutter wear and reduced need for manual feed rate adjustment. In the end manufacturers benefit from increased productivity and faster time-to-market.

However, determining and setting the optimum feed rate has traditionally presented NC programmers and machinists with a number of problems. Because an incorrect estimate can break the cutting tool, damage the fixture, and scrap the part – usually only one or two conservative feed rates are used. Typically, the 'safe' feed rates chosen are a compromise between tool life, cycle time and the worst-case cutting condition encountered.

These 'worst-case' feed rates are fine for the cuts which remove the largest amount of material or encounter the worst cutting conditions. Unfortunately, these slow, poorly controlled speeds waste time, increase manufacturing costs, and create poor cutting conditions elsewhere on the part.

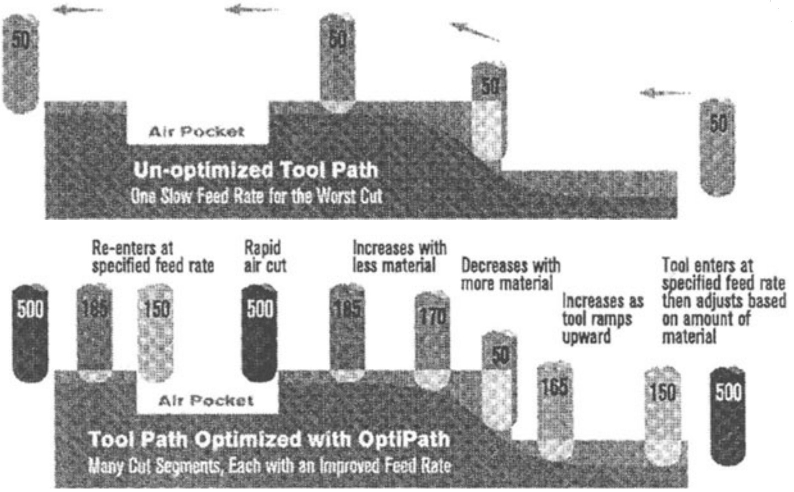

Figure 1. Unoptimized tool path vs. optimized tool path

CAM software does not provide the in-process material information necessary to determine optimum feed rates for each individual cut. And many CAM systems have limited cut patterns that do not fit the workpiece geometry. Their machining strategies and cut patterns are not very efficient for common operations such as open boundaries, roughing cuts on complex shapes, complex pocketing, or planar roughing on mold cavities or cores.

Cutters often waste a lot of time "cutting air" or feeding slowly across previously machined surfaces of the part, in contact with it, but not removing any material. Additionally, an automatically generated tool path may plunge the cutter into material at an incorrect or inefficient angle. The end results can include excessive machining time, bad workpiece finishes, increased cutter wear, and broken tools.

CAM systems do not show the changes as the tool path is applied to the workpiece. It is therefore very difficult for the programmer to visualize the in-process material in an attempt to select the best feed rate for a particular cut. Even if the NC programmer somehow knows the optimal feed rates to use for each individual cut, inserting them into the tool path program is time consuming and error prone. And for large tool paths associated with sculptured surfaces, it is extremely impractical, if not impossible, to manually edit the feed rate changes into the NC program.

The automatic feed rate optimization capabilities of VERICUT work on a simple premise – feed rates increase as less material is being removed and decrease as more material is being removed. Cutting motions are divided into segments. Based on the amount of material removed, the software determines the ideal feed rate for each segment. Without changing the trajectory, the updated information is automatically applied to a new tool path.

Different types of optimization methods are available for different stages of machining. During planar roughing, material is removed at a constant depth, but the width of cut varies greatly. To achieve the best feed rate, the software takes into account the depth of cut and the percent of the cutter width buried in material. The software determines the amount of material removed in each segment of the tool path. It then assigns the best feed rate using the information supplied by the NC programmer and/or machine tool operator.

Semi-finish cutting is typically characterized by varying cutter loads as the tool profiles through the rough cuts to near net shape. Here, it is not as important to analyze depth and width of the cut, but rather the amount of material in contact with the cutter and the angle of the cut along the tool axis. To achieve a smooth cut, the software optimizes feed rates to maintain a constant volume removal rate. Along with a maximum volume removal rate, the contact area and angle are used to determine the appropriate feed rate for each segment of the cut. Therefore, the feed rates continually change over the course of the cut in order to maintain a constant cutting load.

Optimizing the finish pass involves optimizing the spindle speed (RPM) and feed rate to maintain a constant chip load, or feed per tooth (FPT). Depending on machine capabilities, this produces the best finish while cutting at the fastest possible feed rates. The software maintains a constant surface speed and FPT by adjusting the RPM and feed rate. The software factors the diameter of the tool in contact with material together with the constant surface speed to determine the proper RPM. It uses the calculated RPM, FPT, and the number of teeth to calculate the ideal feed rate. Tool paths optimized to maintain a constant FPT are useful in high speed machining where the tool is removing small amounts of material. The constant FPT produces consistent tool marks. The constant surface speed produces a better finish due to improved cutting action.

The ability to simulate control-based acceleration and deceleration during direction changes is also an important ingredient to optimizing NC program feed rates. First, it helps the NC verification software to more accurately optimize feed rates because it takes into account the changes in as each axis accelerates and decelerates. Secondly, it enables the software to simulate the machine's true feed rates. With this information, the software is able to automatically modify the feed rates based on the physical abilities of the machine tool.

6.1 Optimization benchmark

A benchmark by Kryle Machine Tools International Ltd. and Seco Tools (UK) Ltd. to demonstrates the benefits of using the manufacturing model to optimize NC program feed rates.

A Kryle 'tool room specification' VMC 700M equipped with a Mitsubishi M530 MC CNC control with a high-speed Ethernet connection was used. NC data was streamed over the

Ethernet link during the cutting process from a 166 MHz PC. G61.1 positive stop mode was used to maintain accuracy. Seco Micro Turbo milling cutters were used for both roughing and finishing operations.

A part was first machined with a program using the originally programmed feeds and speeds. The roughing program used a single feed rate of 1 meter / minute and took 67.9 minutes to complete. The semi-finishing cycle time was 47.6 minutes. Areas of inefficiency in the program (including long periods of light or spring cutting mixed with short periods of heavy cutting) were easily identified.

The part was then cut using an optimized program. The optimized program contained feed rates varying from 1 meter – 10 meters/ minute in order to maintain a consistent material removal rate. The roughing operation was completed in 36.3 minutes. The time savings on the semi-finishing operation was even more marked, with an optimized time of 19.8 minutes.

7. OTHER USES FOR THE MANUFACTURING MODEL

Using VERICUT to create the manufacturing model and improve feed rates also enables the manufacturer to provide other software applications detailed information on the current cutting conditions of any NC milling operation. A German aerospace manufacturer machines very large, thinwall (1 mm) aluminum parts at high rates of speed. Occasionally, the combination of part geometry, cutting direction, and cutter wear causes excess heat to build up in the workpiece. That heat was causing thermal damage to some very expensive parts. The company's research and development department responded by writing a thermal analysis program. With the program, they could feed in data such as type of tool material, coolant, ambient air temperature, cutter geometry, cutter wear, material thermal characteristics, material thickness around the cutter, etc. for a particular cut. The program would then output the heat transfer in the material at that location along the cutter path. However, they had no way of constantly feeding this information into the analysis program for the entire tool path.

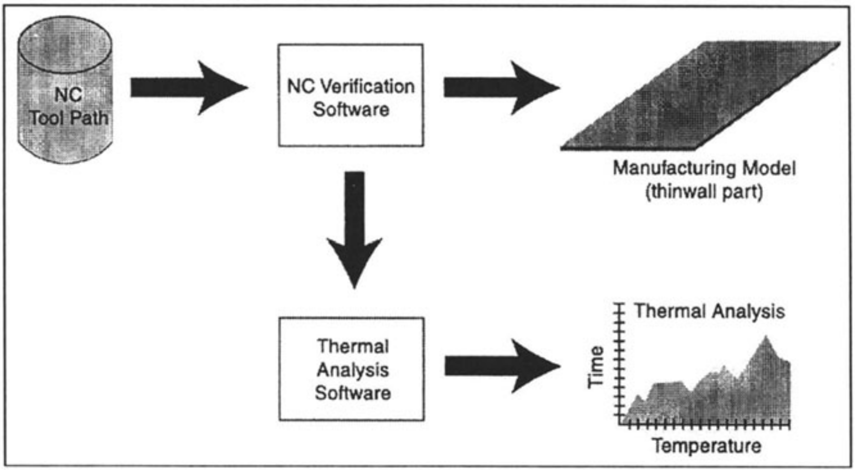

Figure 2. Thermal analysis – NC verification software datalink

The company was an avid user of VERICUT. Consulting with CGTech, they determined the information they needed was being generated as they verified their parts. An inter-process communication channel was set-up between VERICUT and the analysis program. With this setup, engineers now simultaneously watch the material removal simulation and monitor the heat transfer as the cutter moves through material. This ensures correct cutting of the aluminum structures and no workpiece damage due to the excessive heat transfer from the cutting process.

8. SUMMARY

This paper presents uses for an electronic "manufacturing model" in the NC machining environment. Accurate representation of the tool path (including NURBS interpolation, acceleration/deceleration, etc.) is a pre-requisite, especially in the context of complex surface machining. In addition to checking the validity of the tool path, the manufacturing model enables programmers to optimize feed rates in order to save time and improve part quality. The very process of creating the manufacturing model generates information that can be used in alternate applications or subsequent operations.