AC 2008-1363: HIGH PERFORMANCE MACHINING: A PRACTICAL APPROACH TO HIGH-SPEED MACHINING

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High Performance Machining: A Practical Approach to High-Speed Machining

Abstract

High-speed machining (HSM) has become a popular topic in CNC machining methodology in recent years. Simply defined, high-speed machining is a methodology to improve machining throughput by using higher-than-normal spindle speeds coupled with extraordinarily high feed rates without compromising the quality of the finished part. However, in practice, HSM is not a straightforward methodology to implement. In addition to the higher spindle speeds, numerous other factors like feed, chip loading, width and depth of cut, cutter path, tooling, machine construction, CNC-machine controls and CAM software all impact the HSM process. Most conventional CNC machines are equipped with a spindle with lower rpm limits (under 12,000 rpm), so the term "high performance machining" is adopted (HPM). Applying HPM methodology requires the manufacturing engineer to possess in-depth knowledge of the limits of the CNC machine and how to work around them. An initial investment into discovering the limits of any CNC machine is critical to applying HSM techniques to non-specialized CNC machines to obtain high performance machining. This paper briefly addresses the basic concepts of HSM. Then a methodology taught at Arizona State University for systematically determining the high performance machining envelope for a CNC machine is described. A student-implemented case study of this methodology resulting in significant performance gains of machining an automotive part is presented.

Introduction

Current machining methodology is largely experience-based in that much of the knowledge has been handed-down from machinist to machinist via apprenticeships or on-the-job training. The traditional approach to machining often has problems solved by reducing the cutting speed and/or reducing the amount of material being cut[1]. This approach results in cutting parameters that are discovered through trial and error and are typically very conservative. Even when manufacturing education programs teach students to utilize references like Machinery's Handbook[3], machining parameters are somewhat conservative.

Arizona State University manufacturing faculty believe it is important that manufacturing engineers interested in machining understand high performance machining, particularly as applied to conventional machine tools. Thus, their program teaches this content to interested seniors and graduate students. Such knowledge enables manufacturers to improve throughput and increase competitiveness without a significant investment in new machine tools.

Typically, high-speed machining (HSM) is achieved by using small cut depths at very high spindle speeds (often over 20,000 RPM) and aggressive chip loads without a degragration of part accuracy or quality[2]. Maintaining a light cut depth allows for high feedrates while avoiding damage to the workpiece, spindle and cutter. A common pitfall common to first-time adopters of

HSM methodology is the tendency to go overboard and make numerous light passes at extremely small axial depths[4]. This strategy is often less efficient than taking fewer passes since the increase in the overall toolpath length exceeds the gains from using a high feedrate.

Successful application of high-speed machining can be reduced to three key elements: the computer-aided machining (CAM) programming, the CNC machine and tooling[5]. All three elements are closely inter-related, and the right combination leads to productivity gains, cost reduction and improved quality. It is also very easy to get the combination disastrously wrong, generating waste very quickly via mechanisms like tool breakage or excessive chatter.

Programming is an important aspect of HSM. Toolpath and feedrate optimization allows for the optimum cutting path to be generated in order to maximize machine throughput and productivity. Other features like trochordial path generation minimizes tool loading while maintaining a high cutting speed, thereby improving tool wear characteristics. The physical characteristics of the CNC machine also play an important role in the successful application of HSM methodologies. A well-built CNC machine has high rigidity and precision ways resistant to vibration.

With HSM, tooling becomes even more important due to number of issues. Higher speeds mean tooling hardware must be both balanced and rigid (discussed in more depth later). Also, chip formation from HSM processes starts to vary from traditional expectations.

Programming techniques are also different. For example, trochordial path generation is beneficial in HSM. The trochordial toolpath transforms a straight-line toolpath into a series of circular arc toolpaths with a smaller tool and HSM machining parameters. This allows a smaller tool to be used, and is useful especially in slotting operations, where larger tools may demonstrate cooling issues. Using the smaller tool, greater clearance is available for chip evacuation and cutting fluid access. This method of cutting results in an increased tool life.

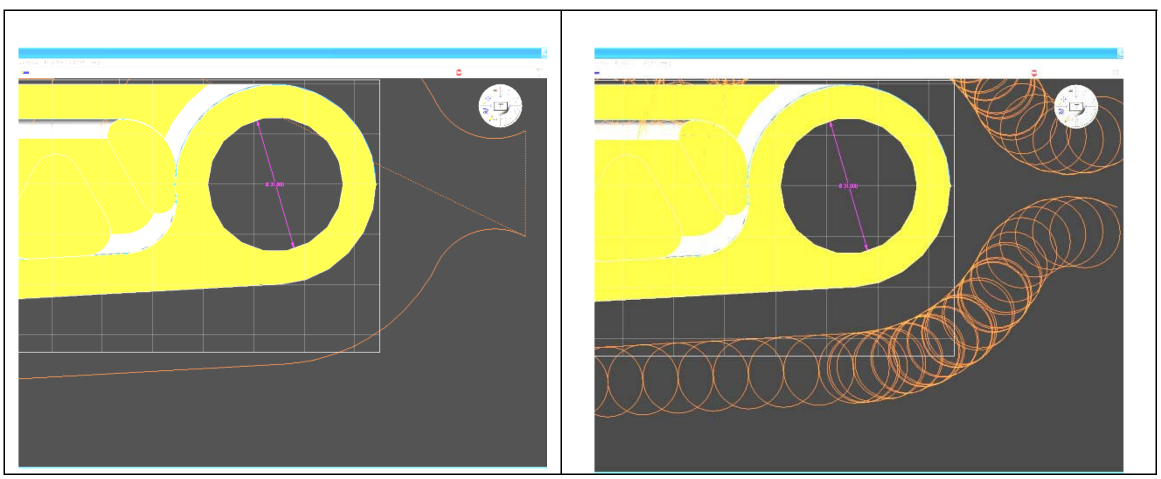


Figure 1
Traditional toolpath (left) versus trochordial toolpath (right)[6]

Since the focus is on using existing, conventional machine tools to achieve HPM, it is worthwhile to review the factors in a CNC machine that play a role in determining the HPM capability of the machine. This information helps manufacturing engineers judge the suitability of their machine (or a new machine) for HPM.

The rigidity of the CNC machine affects how the machine responds to vibration. The effects of vibration become more pronounced with HSM processes. A more rigid machine vibrates less and improves tool life by ensuring an even chip loading, while reducing the propensity for chatter to occur. Machine rigidity is therefore critical when applying HSM methodologies. In short, the more rigid the machine, the better its suitability for HPM.

Typically, HSM-optimized machines use small to medium sized toolholders, and feature direct drive spindle motors. A spindle with a smaller toolholder taper has significantly less mass than a larger spindle. The reduced rotating mass improves the dynamics of the spindle, allowing the CNC control system to control the spindle speed more accurately[7]. Similarly, direct-drive spindles, which eliminate the use of a gearbox, improves the dynamics of the spindle and are better suited to HPM.

Because of the higher speeds, the servo motors have to be able to keep up with the higher speeds and loads. In addition, axial acceleration is critical during abrupt toolpath direction changes. It is desirable that the CNC machine can achieve an axial acceleration of 1.2G to 2.0G with real-time closed-loop positioning throughout the range of cutting speeds[5].

The CNC control features conducive to applying HPM methodologies features include: high speed program data storage, block look ahead, constant surface feed rate, automatic acceleration/deceleration control, and high speed/high precision contouring control. The capacity of the CNC control's program memory needs to be large enough to cope with large HSM-optimized programs. Running through a serial DNC/DNC2 interface becomes impractical because the data rate required by the HSM process is much higher than the serial interface can handle. When this occurs, the CNC machine literally "runs out of program" midway when the program is run. Add-on storage devices like hard disks and USB flash memory act as a secondary storage area for large programs, and allow the large programs to be run directly out of secondary storage. Some control systems are equipped with Ethernet capability, and large programs can be transferred back and forth to the control through the office network via standard file transfer protocols.

Modern CNC controls come with block look ahead where the controller loads in multiple lines (typically 30 or more lines) of CNC code ahead of the current code block being executed. The pre-loaded blocks are preprocessed by the CNC controller, allowing it to adjust the optimum feedrate for the projected toolpath, and eliminate inherent delays in the servo system, which increase with higher feedrates.

Modern CNC controllers are able to automatically maintain a constant surface feedrate for a toolpath. This feature helps HPM by maintaining a constant cutting load, improving surface finish, tool life, and reduces the probability of tool chatter.

At high cutting rates, abrupt direction changes can cause a loss of accuracy and degradation in surface finish[5]. To compensate, CNC controllers include automatic acceleration and deceleration features. Using block lookahead, the CNC control identifies the abrupt toolpath changes by determining the extent of direction (by calculating the tangential change in direction), and automatically accelerates/decelerates the table/workpiece from the programmed feedrate before the change in direction. The figure below illustrates this technique.

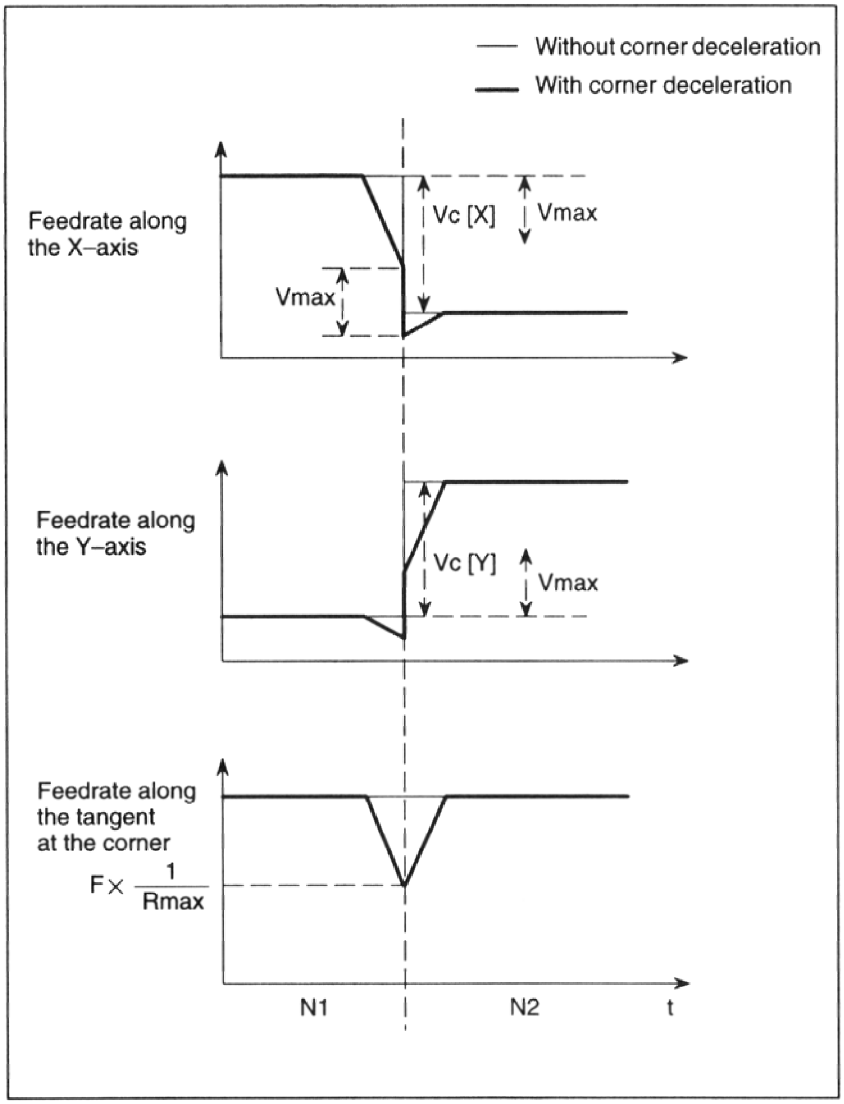


Figure 2
X & Y axis acceleration/deceleration during 90-degree toolpath direction change[8]

In HPM, the toolpath may start to deviate from the programmed toolpath due to physical limitations (maximum acceleration/deceleration characteristics) of the machine. High speed, precision contour control takes closed loop positioning feedback to a higher level by actively monitoring the position of the tool and comparing it to the programmed toolpath and cutting speed. If the control is unable to maintain the positioning accuracy for programmed path and feedrate, the cutting feedrate is dynamically reduced. The reduced feedrate allows the tool to be positioned accurately along the toolpath.

In HPM's higher speeds, feeds, and more aggressive cut parameters, tool wear is accelerated and chatter is more likely to happen. Care has to be taken when mounting the tools in the toolholders and tools must be mounted at the minimum length required for the process. Typically, carbide tooling is ideal for HPM applications because of the increased rigidity of the cutter (resulting in better surface finish) and longer tool life.

Well-designed, rigid toolholders are equally important in HPM applications since they form the interface between the CNC machine's spindle and the tool. In addition to rigidity, toolholder balance is important. However, special, expensive toolholders are not always necessary when doing HPM with conventional machine tools. Weldon shank toolholders should not be used while collet toolholders, milling toolholders with a collapsible bore, shrink-fit toolholders, hydraulic toolholders, and shell/face mill toolholders can perform well. However, shrink-fit toolholders are expensive and hydraulic toolholders can be somewhat fragile.

High Performance Machining Adoption Methodology

A systematic approach is taught for applying HPM methodologies in order to reduce the amount of trial-and-error required. The steps in transitioning an existing process to a HPM process are as follows.

1. Determine the performance envelope of the CNC machine, tooling limitations, and cutting performance baselines.
2. Evaluate current processes and identify efficiency pitfalls and potential areas where the current process can be improved.
3. Re-write CNC code to optimize the program.
4. Perform iterative test-runs while monitoring quality, tool wear, and cycle times.
5. Finalize changes by incorporating data from the test runs into the program.
6. Optimize programs after finalization to further improve performance.

A description of these six steps as taught at Arizona State University follows. Then a case study implemented by a student is provided.

<u>Determining the machine tool performance envelope</u>. The first step is to learn the limitations of the machine and tooling. The torque and power output characteristics of the machine should be studied using manufacturer-supplied charts. (The data and examples below are for the Fanuc Robodrill α-T14iAL used in the case study reported later in the paper). Here the goal is to achieve a maximum throughput for the CNC machine by making full use of the power available, including running the machine spindle at the 10-minute high-power rating for bursts under 4 minutes (this machine has a relatively low-powered spindle motor with a low maximum rpm).

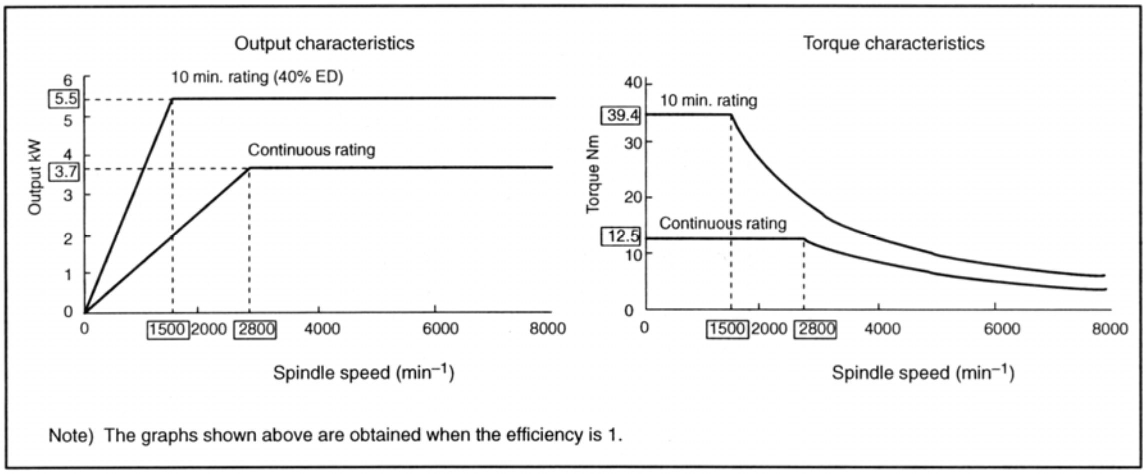


Figure 3. Spindle motor performance characteristics[9]

Test cuts should be performed with each of the commonly used tools in various processes, and the performance of the tool recorded for each different feedrate, cut depth and cut width. This allows determination of the targeted cutting parameters. Spindle load is typically used as the performance metric, but the finish can also be studied to determine the best of the each cutting parameter set. The results are tabulated in charts similar to the one below:

Table 1. Example baseline cutting characteristics

Tool #106 – 2” Face Mill, 4 FLT 45° Lead						
RPM	Feed Rate (mm/min)	Feed (in/min)	Cut Width (mm)	Cut Depth (mm)	Spindle Load	Remarks
8000	2540	100	50.8	2.00	33%	Good finish
8000	10160	400	50.8	2.00	120%	
8000	11430	450	50.8	2.00	137%	
8000	11430	450	35.0	3.00	134%	
8000	12192	480	35.0	3.00	162%	Spindle O/L
8000	11430	450	35.0	3.50	146%	
8000	11430	450	25.4	3.50	106%	

<u>Evaluate current processes</u>. Upon selecting a target part or family of similar parts, run parts using the original CNC code and record the spindle loads as the part is run. The cutting paths should be actively monitored to see if the toolpaths are optimal. Also, surface finish on the part surfaces should be evaluated. This information is used to determine where the existing process can be improved.

<u>Rewrite the CNC program</u>. Using data gathered from the machine performance testing, process evaluation and baseline cutting tests, the CNC program is re-written to make full use of the capabilities of the machine and cutting tools. Using a computer-aided manufacturing (CAM) package, the part program should use the new feeds, speeds, and cutting parameters obtained from testing. Toolpaths should also be studied using the simulation feature of the CAM software to provide additional insight to potential problems that may arise during the machining process. Use the operation summary report available in most CAM software to determine the projected run-time. The part program is generated using the appropriate post-processor and opened in a

text editor for manual code cleanup. In this last step, machine specific control-commands should be added to the program to enable HPM specific features like block look-ahead, high speed precision control, and acceleration/deceleration control.

Perform iterative test-runs. Test runs should be made to verify the new program and the expected productivity gains. During these test runs, the speed and feeds should be varied while the machine load is monitored. Often the feedrate can be increased without compromising part finish, and, conversely the feedrate may have to be lowered slightly to prevent tool chatter. Any changes should be applied to the program with a text editor, and the process repeated on a new part to verify the changes.

Finalize program. After the test runs are completed and programs changes verified, the CNC program should be finalized. Documentation of the program, tooling package, and machine parameters should be completed.

Optimize program. As with any manufacturing system, the machine and parts should be monitored. Due to tool wear, the machine spindle motor load will progressively increase as the tooling wears with the resulting danger of exceeding the load limit of the CNC machine. This can be avoided by setting up an allowance (reduction) for the cutting feedrate. This parameter allowance is determined in-process, by actively monitoring the performance of the tool during subsequent runs of the same part.

HPM Adoption Case Study

This case study was performed on a Fanuc Robodrill αT14i-AL owned by Function7 Engineering[10]. This compact CNC machine was equipped with the Fanuc 16iM-A CNC control system with several HSM-optimized features. The control features a modest 50-block look ahead buffer, AICC precision contour control, as well as flexible high capacity storage using standard ATA/compact flash cards. The part family targeted was a series of aftermarket automotive suspension arms (see Figure 4) and the goal was to increase the efficiency of part manufacture by 50% (reduce machine time by half). The owner believed he had been aggressive in the part programming and machining parameters in the existing processes for the part's manufacture.

Figure 4. Function7 Engineering Suspension Arm Part Family

Each arm is machined out of solid bar of 2.5" x 2.5" billet 7075 aluminum with the overall length of the arms varying between 14.5" and 18.25." The machining processes for the family of parts are similar and consist of two set-ups and related machining sequences, which will be referred to as Operation 1 and Operation 2. The baseline Operation 1 involved 13 tools and an average elapsed time of just less than 56 minutes (data from production runs over 3 months). Operation 2 involved 10 tools and had an average elapsed time of just over 52 minutes.

As shown above (e.g., Figure 3 and Table 1), machine tool performance and baseline cutting data were gathered. Data were gathered for all the tools used in the process plan for the target parts. During the evaluation phase, several programming pitfalls were found. These included several poorly designed toolpaths, poor contour surface finishes and cutting parameters that did not utilize the full capability of the machine. In the redesign step, the information gathered from the process analysis, as well as the machine cutting baseline tables, a new manufacturing process plan and "draft" CNC program were generated. For example, optimizing the face-milling operation by increasing the depth of cut while maintaining a high federate, increasing the peak spindle load to over 140% (projected), provided a significant gain. This change reduced the sub-operation time to about five minutes and 30 seconds from an original time of 12 minutes and 47 seconds. To improve the surface finish on the contoured surfaces, more aggressive feedrates were used and the toolpath was programmed to do bottom-up passes. The CAM software simulation projected the total Operation 1 time to be 22.5 minutes. Test parts were made and found to still have problems on the contoured surfaces. Thus, the feedrates were reduced to improve the finish. After final optimization, the total time for Operation 1 increased to 31 minutes but resulted in better surface finish. Following a similar process, Operation 2 machine time was reduced to less than 24 minutes. Thus, the total machine time for the part was 55 minutes or about 50% of the original time. In addition, finish quality for the part was improved (see Figure 5) with the same tolerance level as the original part.

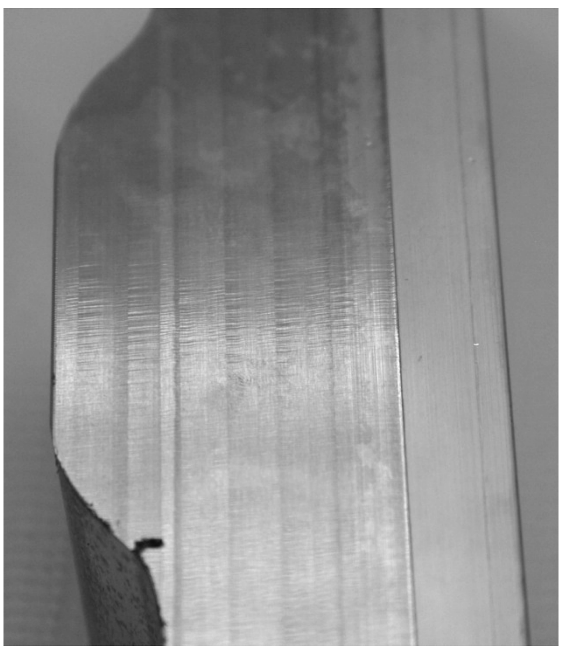
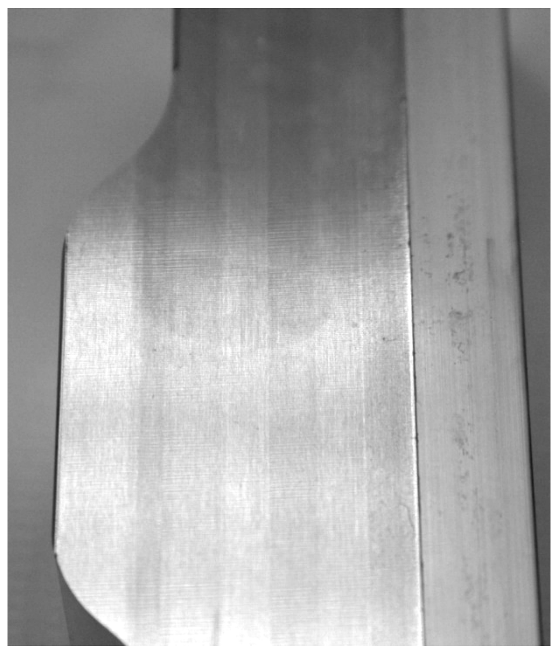
Initial Version	Revised Version
 Contoured surface shows poor surface finish	 Improved surface finish on contoured surface
 Surface quality of profile cutting	 Improved surface finish from revised programming

Figure 5. Part quality comparison of initial and revised processes

Conclusion

When applied properly, the productivity gains from HPM machining can be significant. Benefits from the application of HPM methodologies include; reduced cycle times, improved tool life via trochordial toolpaths, and an overall improvement in surface finish. The application of HPM methodologies to conventional machine tools requires a systematic approach. Without a proper method of determining cutting capabilities to avoid a trial-and-error approach, HPM can quickly becomes an exercise in time and material waste.

The first step in a systematic approach to implementing HPM is to determine the cutting capabilities of the machine. This information can then be used as a cutting performance baseline, and resulting parameters applied to the CAM programming process. After the CNC program is generated via CAM software, further optimization is required by doing a series of test runs.

Even for small-manufacturing runs, this approach can be applied. The performance baselines make a very good starting point to help use the machine's capabilities fully. A well-planned application of HPM can see a 50% or better cycle time reduction, increasing the manufacturing throughput by a factor of two. The time expended in applying HSM methodologies pays off almost immediately, since the performance gains can be applied to manufacturing processes for both existing and new parts.

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