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Self-Tuning Process Monitoring System for Process-Based Product

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Self-Tuning Process Monitoring System for Process-Based Product

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Abstract

The hidden qualities of a product are often revealed in the process. Subsurface material damage, surface cracks, and unusual burr formation can occur during a poorly controlled machining process. Standard post process inspection is costly and may not reveal these conditions. However, by monitoring the proper process parameters, these conditions are readily detectable without incurring the cost of post process inspection. In addition, many unforeseen process anomalies may be detected using an advanced process monitoring system.

This work created a process monitoring system for milling machines which mapped the forces, power, vibration, and acoustic emissions generated during a cutting cycle onto a 3D model of the part being machined. The "hyperpoint overlay" can be analyzed and visualized with VRML (Virtual Reality Modeling Language).

Once the Process Monitoring System is deployed, detailed inspection may be significantly reduced or eliminated. The project deployed a Pro-Engineer to VRML model conversion routine, advanced visualization interface, tool path transformation with mesh generation routine, hyperpoint overlay routine, stable sensor array, sensor calibration routine, and machine calibration methodology.

The technology created in this project can help validate production of WR (War Reserve) components by generating process signatures for products, processes, and lot runs. The signatures of each product can be compared across all products made within and across lot runs to determine if the processes that produced the product are consistently providing superior quality. Furthermore, the qualities of the processes are visibly apparent, since the part model is overlaid with process data. The system was evaluated on three different part productions.

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Nomenclature

VRML .... Virtual Reality Markup Language
LDRD .... Laboratory Directed Research and Development
GUI .... Graphical User Interface
WR ....War Reserve
hyperpoint..Geometric points augmented with additional information
RMS ....Root Mean Square

Process Monitoring System for Process Based Product Validation

Introduction

The traditional method for inspecting the quality and reliability of a machined product is by post process inspection and testing. By contrast, in this LDRD, we developed an on-line, in process hyperpoint signature analysis methodology that will characterize the quality and reliability of a product during manufacturing. A "hyperpoint" is a Cartesian point in space that is augmented with additional information such as force or vibration sensor readings. These hyperpoints are color coded and mapped onto the part model to visually indicate process characteristics in relation to product features. The key innovation is the ability to identify problems in a process rather than the results of a poor process that show up in the product. However, this strategy does place increased emphasis on much more reliable sensor systems. We developed sensor systems that can observe the environment in which they operate and establish the parameters for stabilizing production.

This LDRD combines research on sensors, signal processing, machine intelligence, and CAD solid model manipulation, to facilitate the implementation of process based product validation and advanced process visualization. By using these technologies for "in process" signature analysis of a machining operation's process stability, product-to-product uniformity, material characteristics, and tool condition may be detected and fully visualized. In addition, information obtained in the process monitoring may be used by manufacturing engineers to improve the process; by process engineers to improve product production; and by designers to improve the product design.

Sensor uncertainty, especially in the implementation of multi-sensor systems, is a key problem. This is especially true for material removal processes where a large amount of uncertainty is introduced by the peculiarities of the process and environmental changes during processing (material properties, for example). In precision manufacturing, with its very low material removal rates, the process uncertainty can be quite high. There are few commercially available sensor systems that function reliably in the manufacturing environment.

The sensor development work concentrated on sensing technologies that extend the capabilities of existing sensors. Added sensor capabilities are needed in finishing operations where metal removal rates are low, and force and torque-based techniques fail to provide adequate sensitivity. Added capabilities are also needed for phenomena such as tool wear and fracture, where traditional sensors often do not adequately predict the imminent fracture of a tool. The objective of this research was to develop and deploy strategies for sensor implementation in real process monitoring to verify process stability and product uniformity. This will promote the development of a base technology as well as its evaluation in a realistic environment. In this project the base sensor system was derived from a tool condition monitoring system. The work involved machine modification, sensor application, signal processing, machine calibration, design model manipulation, and process data manipulation. Each milestone proved to be a useful tool in-and-of-itself.

2. Equipment

The target of the process monitoring system was a three axis Haas milling machine. The three axes milling machine was modified for a previous project so that it may be operated with its original controller, or a retrofitted open architecture controller.

Figure 1 Haas Milling Machine with Process Monitoring System

An industrial tool monitoring system was modified and used as the basis for the process monitoring system. The system has sensors for spindle power, vibration, and acoustic emissions. In addition, a six-axes Kistler dynamometer was added of the six axes, only the three force axes were used. The position of the machine was monitored using a four axes encoder interface card. All sensor signals were read by a PC with a National Instruments data acquisition card. The entire system is very modular, and is transferable to any machine tool.

The spindle power is a true power measurement that multiplies the actual voltage to the motor by the actual current to the motor.

The acoustic sensor has a bandwidth of 450 kHz and a low cutoff range of 50 kHz. The system electronically RMS's the acoustic magnitude for three frequency bands. The bands are 50 kHz-80kHz, 80kHz-140kHz, and 240kHz-450kHz.

The vibration sensor has a bandwidth of 14kHz and a low cut off of 10 Hz. Similar to the acoustic sensor, the vibration sensor output is electronically RMS'ed in four frequency bands. The bands are 10Hz-100Hz, 100Hz-600Hz, 600Hz-3kHz, and 3kHz-14kHz.

The force sensor used is a Kistler 9281B table mounted dynamometer with amplifier 9865B. Its force range is +/- 6,402 N (1,439 pounds) in X and Y, +/- 12,987 N (2,920 pounds) in Z, and +/- 500 Nm torque in X, Y, and +/- 1000 Nm in Z. The usable dynamic range of the system is from 0Hz to 700Hz. Only the three linear components of force were used in this project due to sensor input limitations and the ambiguity associated with torque verses fixturing location (torque read on the dynamometer is dependent on where and how the part being machined is mounted to the dynamometer). The dynamometer system is ruggedized for use in the machining environment. It is water proof, and shock resistant. The cables are shielded both electronically, and mechanically (for hot chip protection). Typical cutting forces in this size of milling machine range from a few pounds to about 500 pounds. Impact forces can reach a few thousand pounds when a cutting tool first makes contact with metal.

This type of dynamometer is not perfectly suited for this application. This dynamometer is made more for the laboratory environment and short experimental runs. The system has large dynamic range and accuracy, and is very stiff; however, is prone to drift and load offsets. In this environment, dynamic range is not extremely important (a few hertz is sufficient), and drift is highly undesirable. A better load cell could be made from strain gauges which are not as prone to drifting and have lower bandwidth. However, such a load cell would have lower stiffness. Furthermore, strain gauge load cells are not readily available for the manufacturing environment.

3. Process Basics

The process monitoring system essentially collects data during a machining process. The data is collected at specified positions in the cutting process. Because of this, the sensor data may be color coded and mapped onto the model of the part. When the mapped data is viewed on the model, there is a clear indication as to where cutting process parameters change with respect to the geometry of the cut.

The system, in monitoring mode, will read the position data every 3 milliseconds and calculate the distance traveled since the last process data values collected. If the distance traveled is equal to or greater than the desired distance increment, the process data will be gathered. This time interval ensures that the maximum error in distance traveled for very fast cutting (>2500 mm/min) will be about 10% of the minimum desired increment (<1mm). However, typical cutting speeds are much less than 2500 mm/min and desired acquisition interval is greater than 1mm. The resulting error is typically less than 1%.

$$100\tfrac{in}{\min}\frac{1\min}{60s}0.003s = 0.005in$$

$$2500\tfrac{mm}{\min}\frac{1\min}{60s}0.003s = 0.125mm$$

4. Software

Some of the program is written for the particular hardware it was developed on, and therefore care must be taken to port the software for generic use.

A web-based utility was created which translates Pro-Engineer models to VRML (Figure 2). This utility allows the user to submit a Pro-Engineer model and automatically receive a VRML model in return.

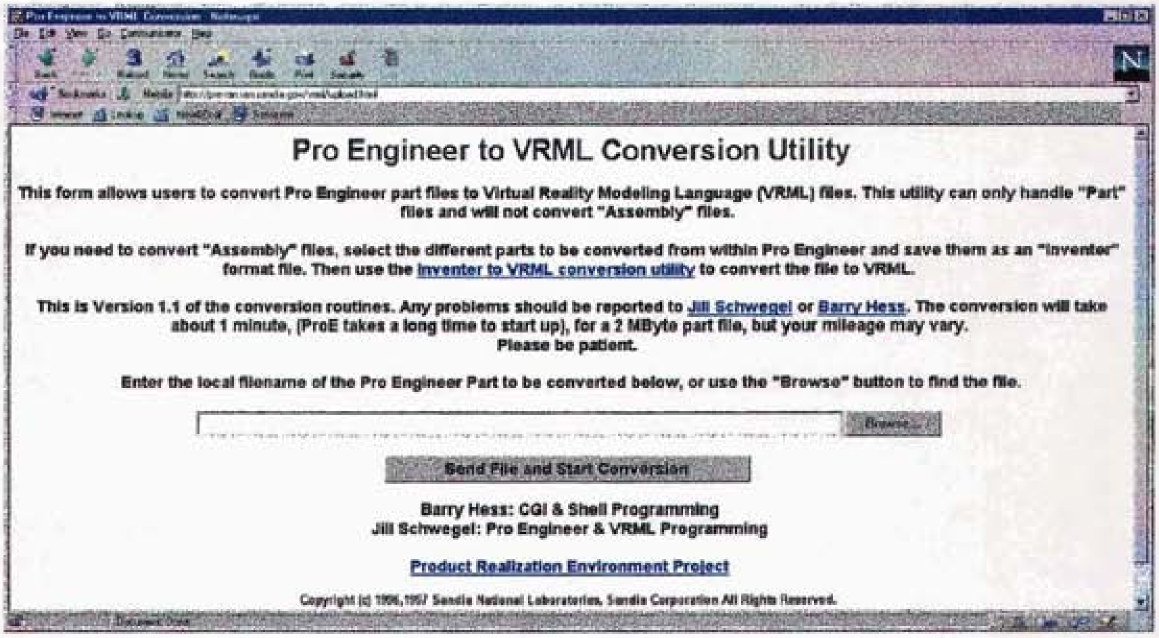

Figure 2 Pro-Engineer to VRML Translator

The advanced visualization interface software is a Windows 95-C program that provides a graphical user interface (GUI) and a data acquisition utility to allow real-time collection and display of sensor data, as well as set up and calibration of sensors. The GUI was developed using Lab Windows ™ that is a product developed by National Instruments to help develop data acquisition programs. The code was cross compiled in Visual C++ for its multi threaded capability and timing. WinRT ™ libraries were used for interrupt handling. The program offers a user interface that allows the operator to setup the force sensors and the distance interval between which data points will be collected. It provides a diagnostic data window pop-up to calibrate and debug the sensor readings. It also provides facilities to start and stop a test run, save data, collect data at a pre-defined distance interval, or collect data in a continuous time mode. The GUI also displays the sensor data in real-time. This facilitates a determination if the system is operating properly.

The process monitoring software has a GUI shown in Figure 3. The GUI shows the present position of the tool, the distance the tool has traveled since the software has been running, and strip charts showing the Power, Force, Vibration, and Acoustic sensor readings. When the software first starts, the strip charts are in "free run" mode. The strip charts will show the sensor readings continuously. The speed of acquisition is not controlled, and the data is not being saved.

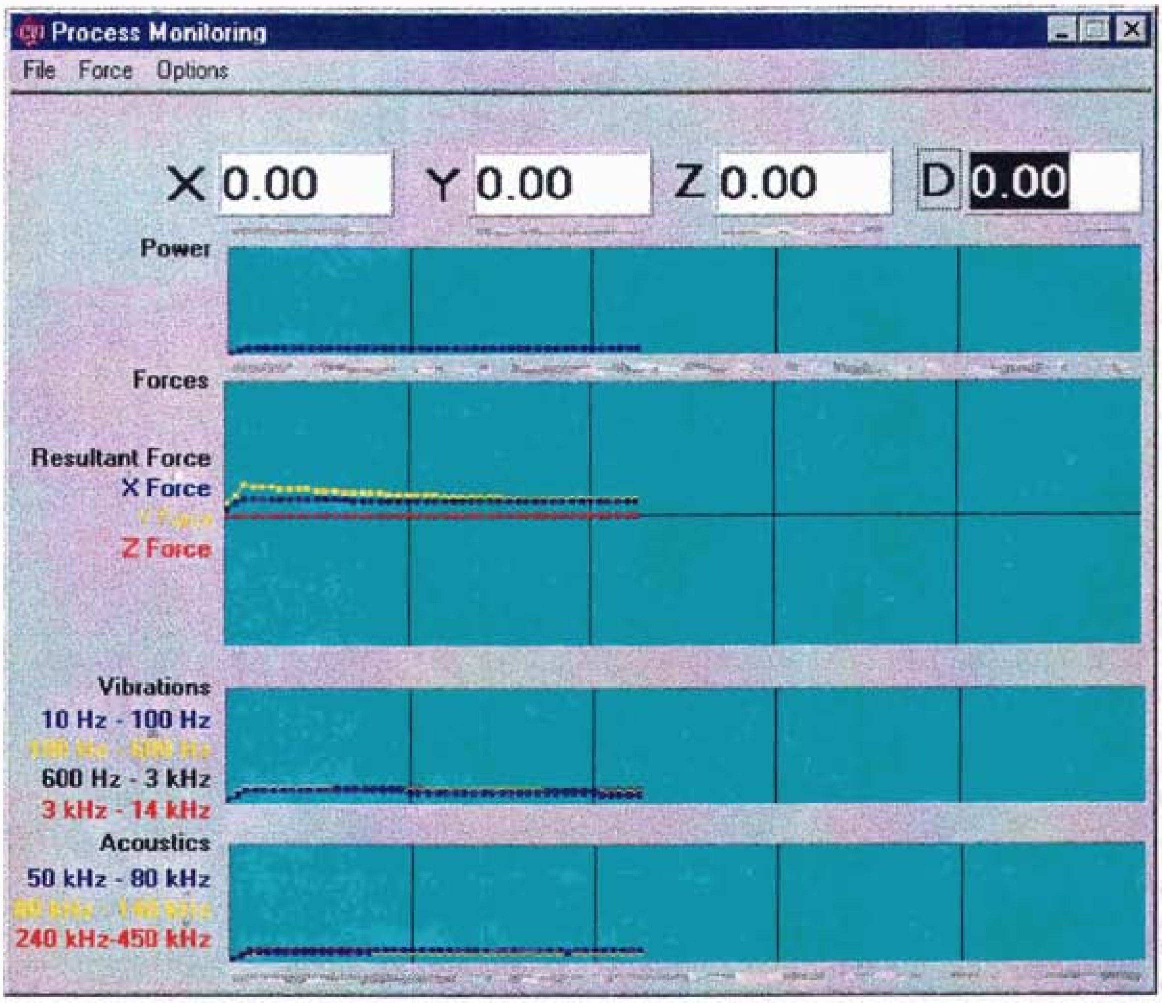

Figure 3 Graphical User Interface

Each of the position and distance data channels may be dynamically edited by double clicking on the fields as shown in Figure 4. This feature is useful to zero out the distances if starting a new monitoring run, or when starting a monitoring run at some position other than zero position and distance.

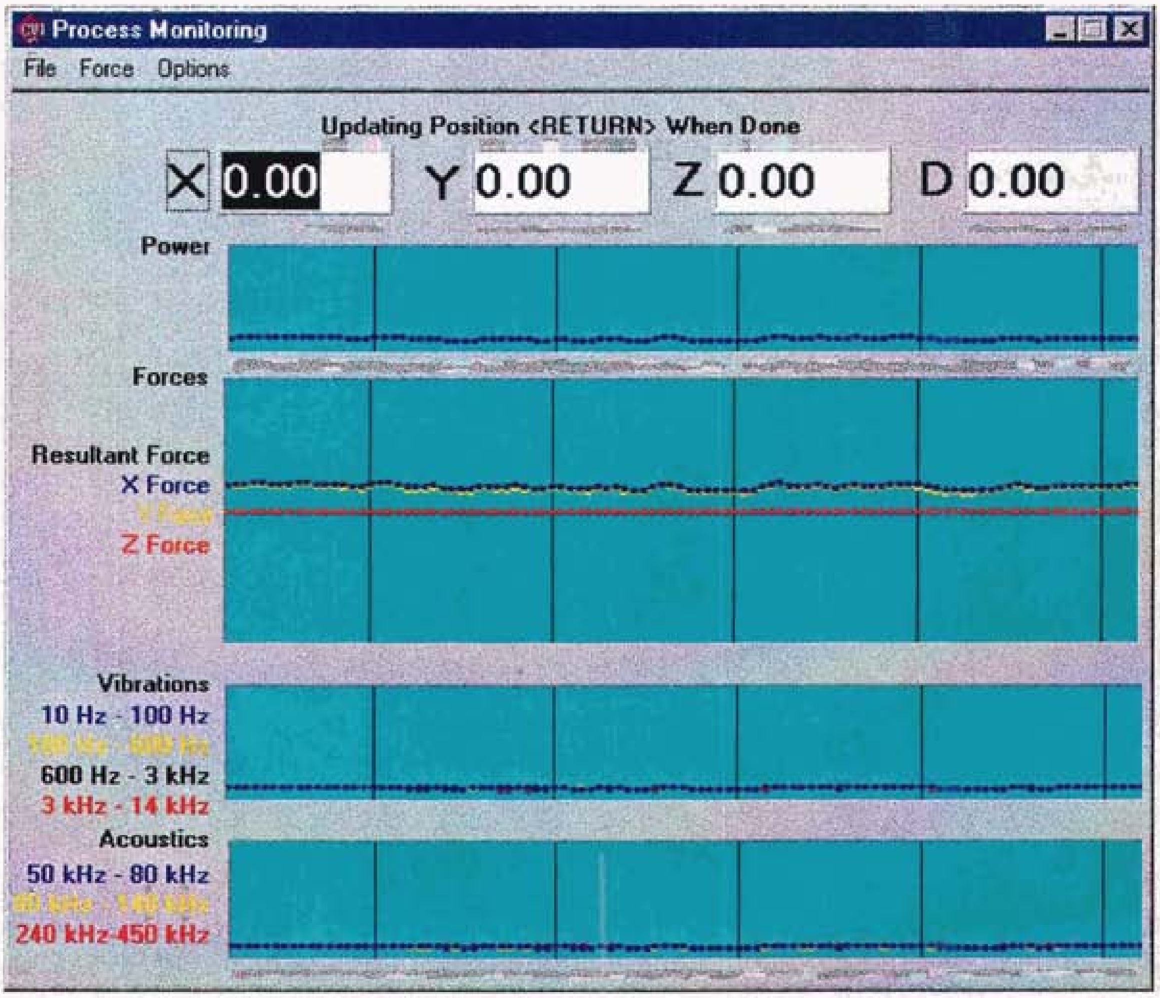

Figure 4 Updating Position

Across the top of the GUI is a menu bar, (shown in Figure 3 and Figure 4). The menu bar contains three menu items. The first menu item is "File," Figure 5. Under the file menu item there are four sub-menu items. "Record Data" begins the process monitoring acquisition. Position data will be gathered in 0.003 sec intervals. The distance traveled will be accumulated. When the distance traveled is equal to or greater than the desired acquisition interval, the analog sensors will be read and recorded.

The "Free Run Record" will collect position and analog data continuously. This feature is useful for debugging since data may be collected without the machine moving. Once acquisition is complete the data may be saved to disk. The "Save Data" window in Figure 6 will pop-up and allows the user to select name and location for the data file. The last sub-menu item is "Quit."

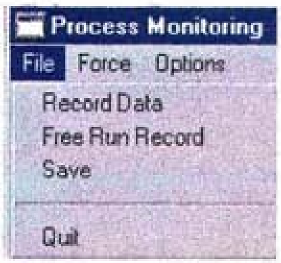

Figure 5 File Menu

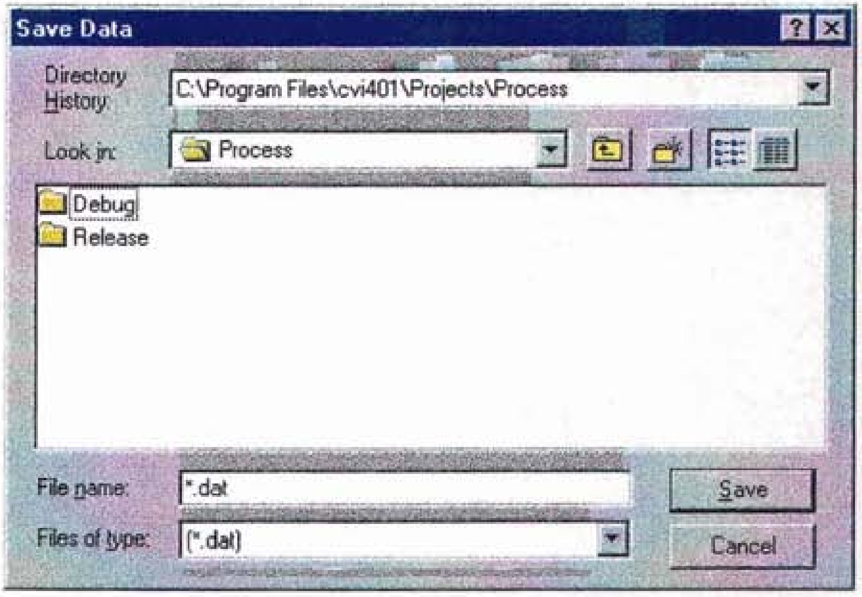

Figure 6 Saving Data

The second menu item is "Force" (Figure 7). This menu item will allow the user to set up the dynamometer for force acquisition. The dynamometer is the most cumbersome sensor and warrants its own menu item. Under the Force menu item there are three sub-menu items. The first sub-menu item is "Time Constant" (Figure 8). The time constant selection may be set to long or short. This will set the rate at which charge will be drained from the charge capacitors that measure the force. The long time constant is best suited for process monitoring since it provides the least noise sensitivity (we are not interested in high frequency force dynamics of the cutting process).

The second and third sub-menu items select the force range for the dynamometer (Figure 9 and Figure 10). The XY force range is approximately twice as sensitive as the Z force range. Trial runs should be made to determine the proper force range setting for each application. However, with a little experience trial runs are not necessary. For instance, after several tests it may be seen that a ½ inch cutter in aluminum making typical cuts will typically create loads less than 100 pounds.

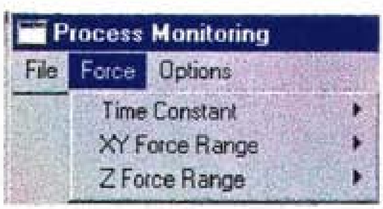

Figure 7 Force Menu

Figure 8 Force time Constant

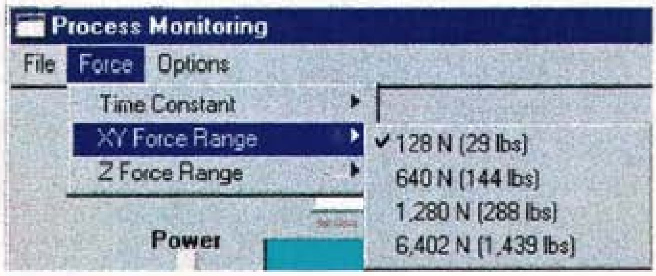

Figure 9 XY Force Range

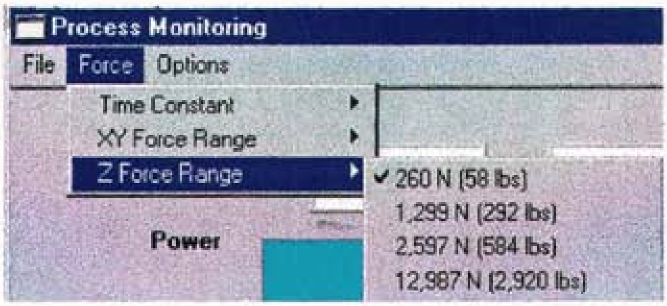

Figure 10 Z Force Range

The last menu item is "Options," (Figure 11). This contains items that will bring up an auxiliary GUI, (Figure 12), or an "Increment" edit window (Figure 13). The auxiliary GUI will show numerical values for all of the analog sensors. This is very useful for calibration and debugging. The "Increment" window allows the user to edit the distance increment at which analog data will be collected.

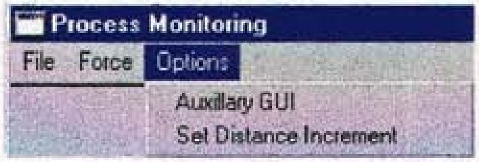

Figure 11 Options Menu

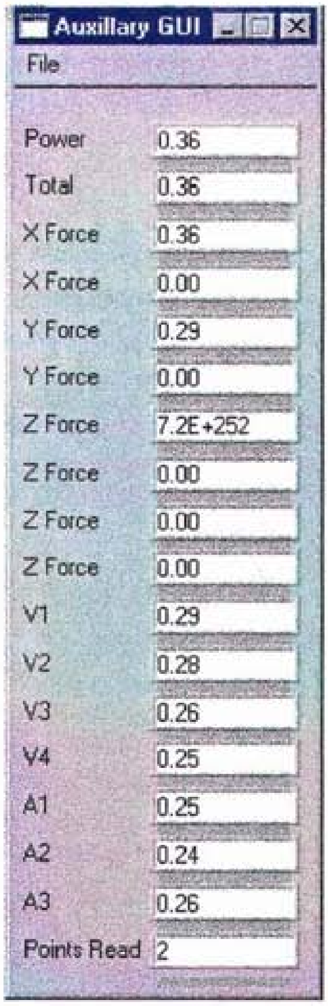

Figure 12 Auxiliary GUI

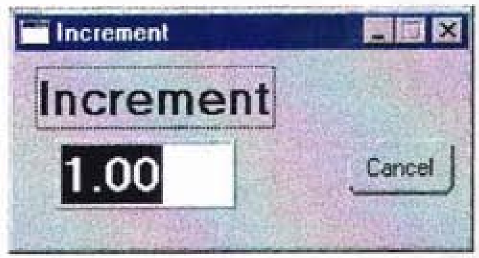

Figure 13 Increment Set Window

Finally, a hyperpoint overlay utility was created which maps the force, torque, vibration, and acoustic hyperpoints to the VRML model of the part. The output of this utility is an augmented VRML model that may be viewed with any VRML viewer.

5. Calibration

Calibrating the sensors is critical to insuring that the information obtained is consistent and meaningful. Power is measured directly through current and voltage, therefore, no calibration is needed. Calibration of the force sensors will be done by applying forces, through a previously calibrated portable dynamometer to the process monitoring dynamometer and noting readings and adjusting discrepancies. The calibration of vibration and acoustics sensors are not economically feasible. Instead, maintaining the factory calibration data and deploying fitness-for-use tests are the most reasonable alternative. For the acoustic sensor, the fitness-for-use test of the acoustic sensor is the pencil break test. Use of a 0.5mm mechanical pencil, the lead is extended 5mm and broken on the acoustic sensor in the center of the sensing region holding the pencil at a 45 degree angle. The reading from the sensor should be recorded. If significant deviation from the baseline test is detected, the sensor is not fit for use.

Machine calibration is critical to insuring that process monitoring will provide a consistent indication of product quality across different machining platforms. The method used to calibrate the machine is a derivative of the method in ASME B5.54-1992 "Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers." The test subsets for this project are: rotating error motion, linear displacement accuracy test, contouring performance test, and machine compliance test.

6. Experimentation

The system was evaluated on three different part productions. The first part design was used to evaluate the sensor sensitivity, (Figure 14). This design involved milling several multi-pass slots into a piece of rectangular aluminum. The machine feeds and speeds, and slot wall thickness were varied for each slot to determine the effect of these parameters on the quality of the part, as well as the values read by the sensor system.

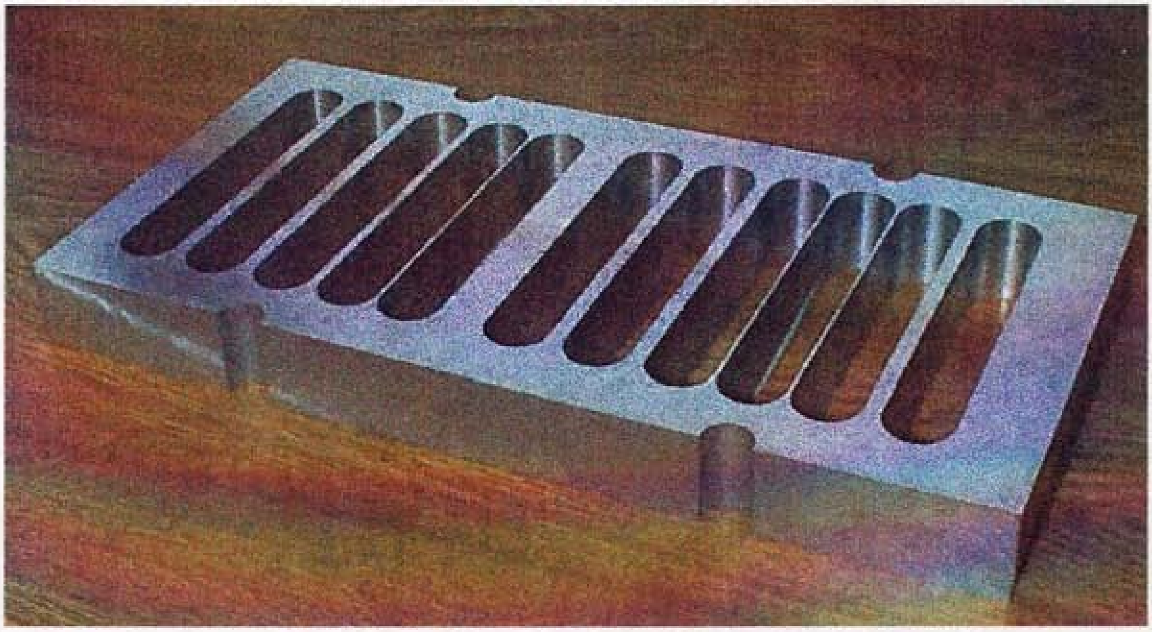

Figure 14 Slotted Part

The next design was an ASME B5.54 specification NAS part known as the "Circle Diamond Square," (Figure 15). This design was needed for other research being done by a visiting professor, but was well suited for examining the usefulness of the process monitoring system.

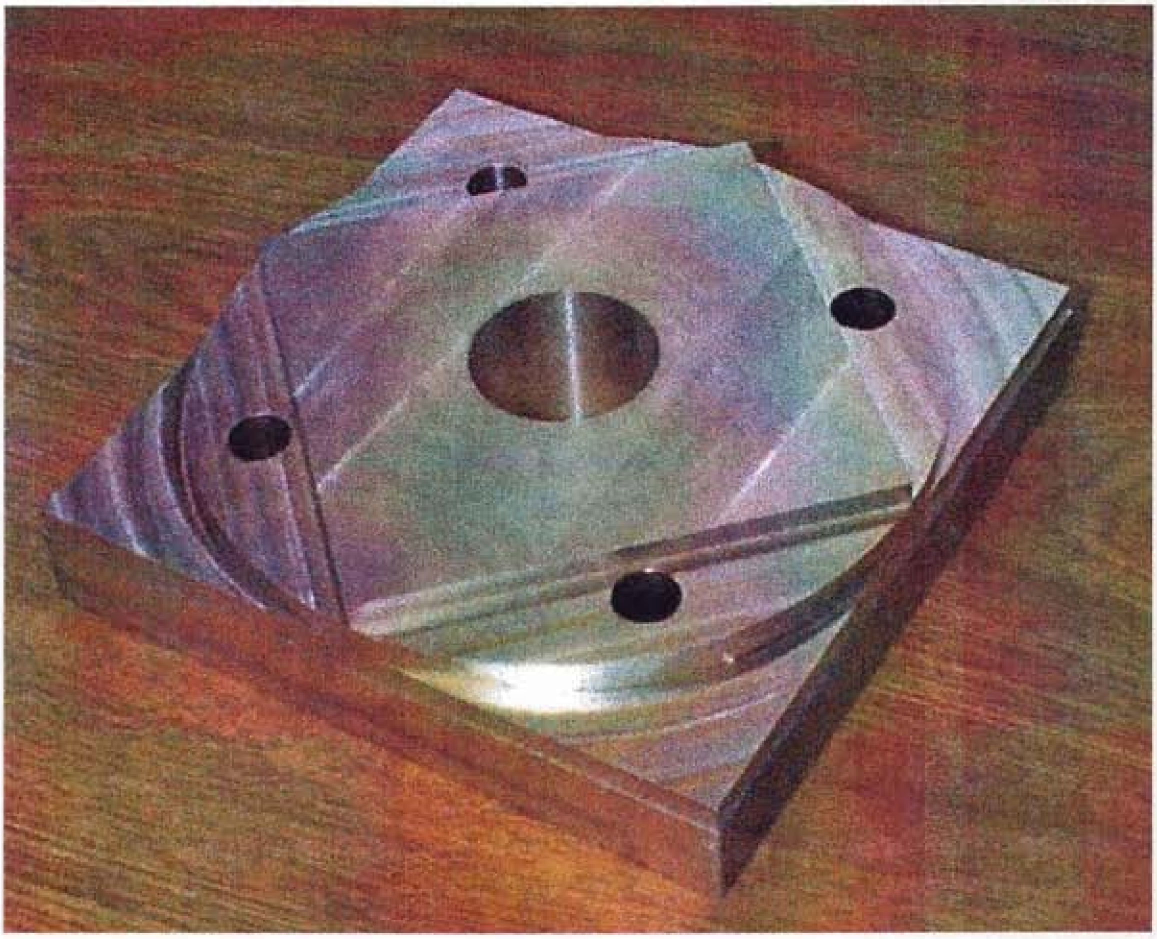

Figure 15 Circle Diamond Square Part

Finally, a design was submitted by the EUVL (Extreme Ultra-Violet Lithography) group. This involved production of a cooling chuck, (Figure 16). The part was produced for customer use, as well as our experimental requirements. Therefore, more parts were produced than required, so that bad parts could be purposely manufactured to verify that the process monitoring system would identify them.

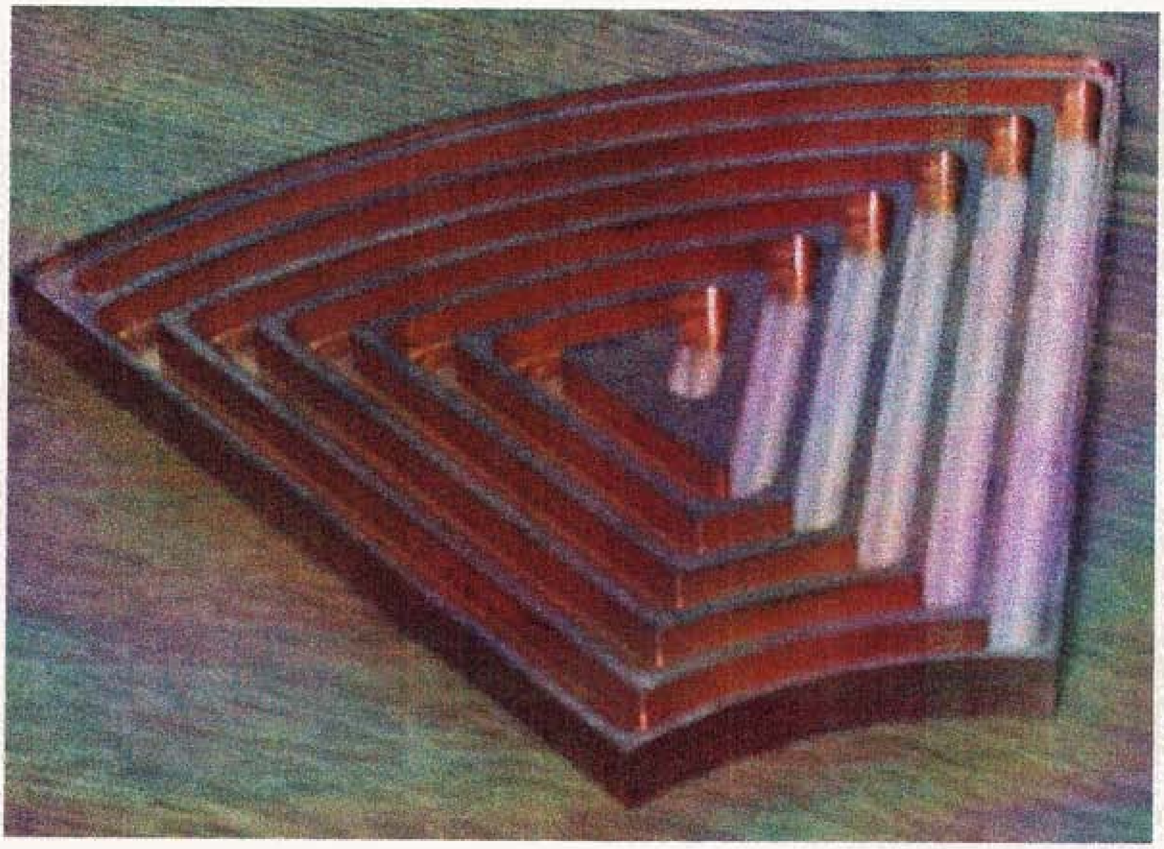

Figure 16 EUVL Part

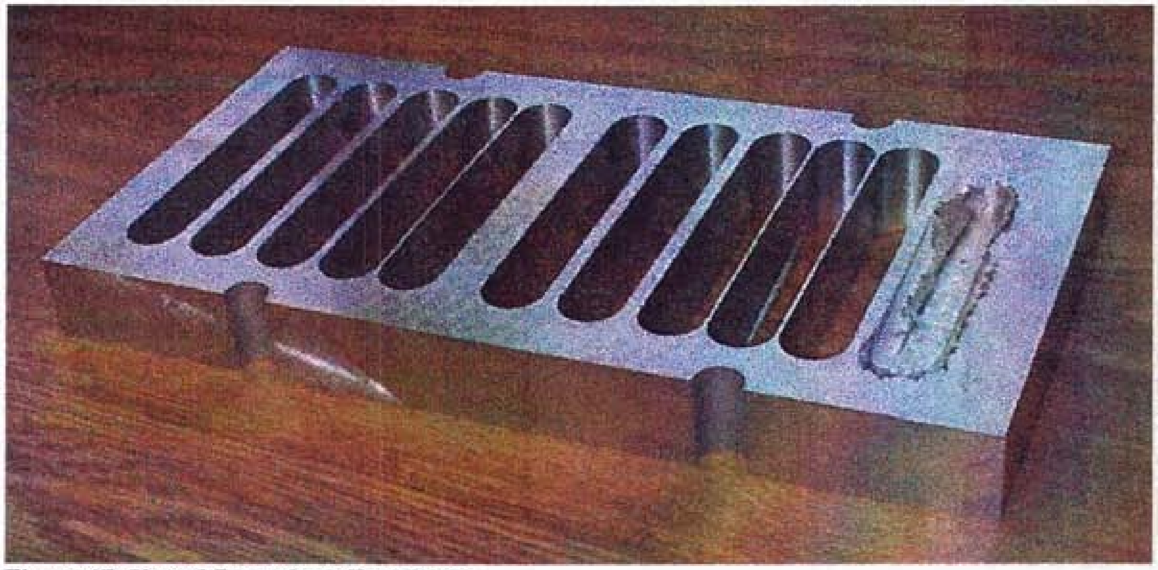

Figure 17 Slotted Part where Tool Broke

The slotted part shows, perhaps, the most interesting information Figure 17—Figure 43. With the slotted part, cutting parameters were varied greatly to exercise the process monitoring system. Not only were cutting feeds (work-piece velocity) and speeds (spindle rpm) varied greatly, but wall thickness were also varied.

The spindle power showed no correlation to spindle speed. This indicates that the spindle had no difficulty cutting the material. Force correlated well to tool breakage. One interesting note is that the tool broke at the red spot in Figure 23 yet the force values are still red-lined after that point, this is due to the error generated by the dynamometer amplifier when the sensor was saturated.

Vibration, on the other hand, showed very interesting information. The first few passes in each slot were fairly benign (consistent and low in magnitude). As the tool made its last pass the vibration increased dramatically. Furthermore, this is most notable in the thin walled slots Figure 43. On the physical part chatter marks are evident at these locations Figure 42. Overall, the vibration sensor revealed the most interesting information.

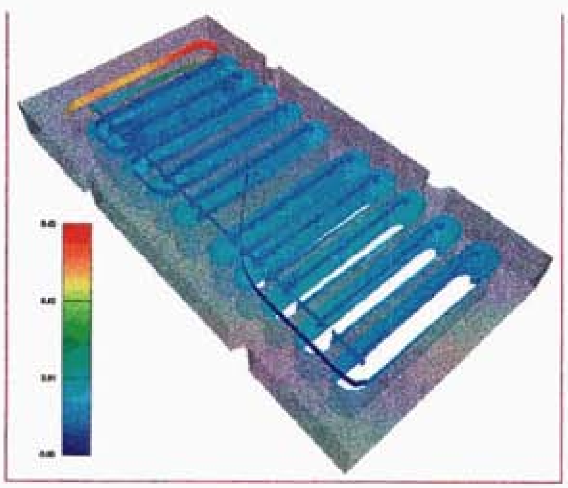

Figure 18 Slotted Part Spindle Power

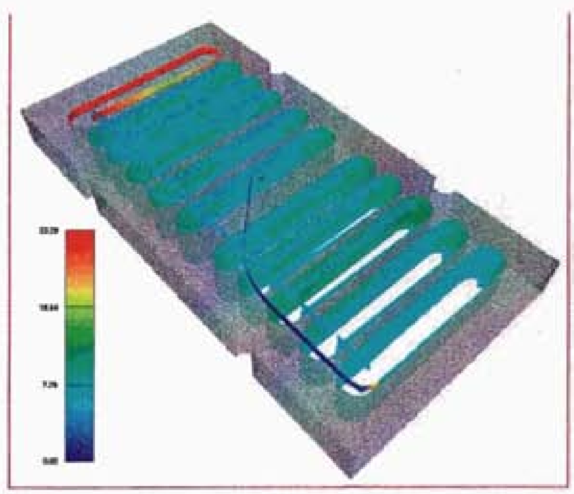

Figure 19 Slotted Part X Force

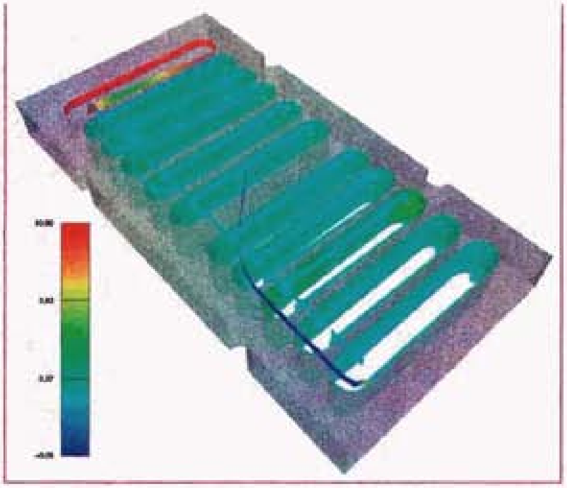

Figure 20 Slotted Part Y Force

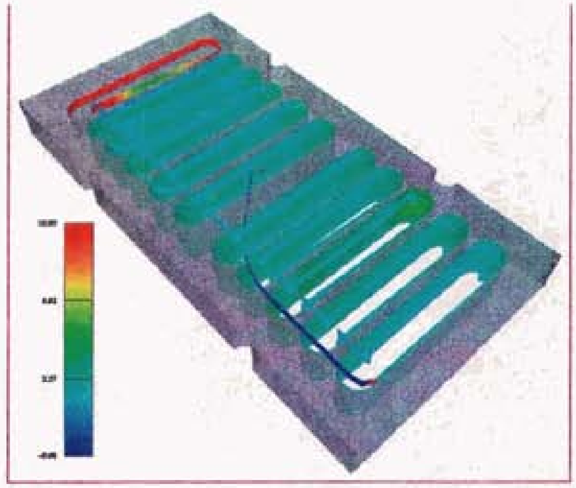

Figure 21 Slotted Part Z Force

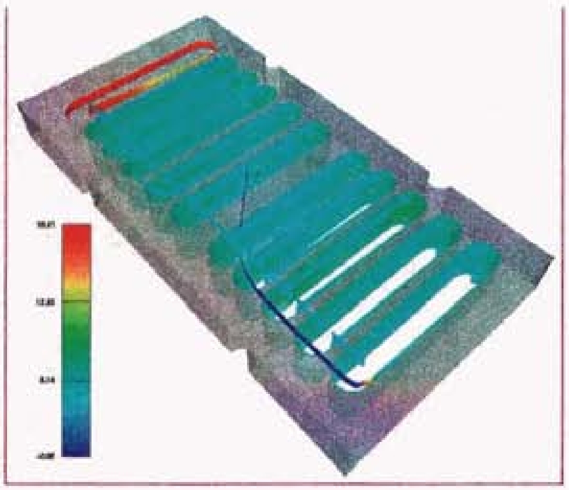

Figure 22 Slotted Part Resultant Force

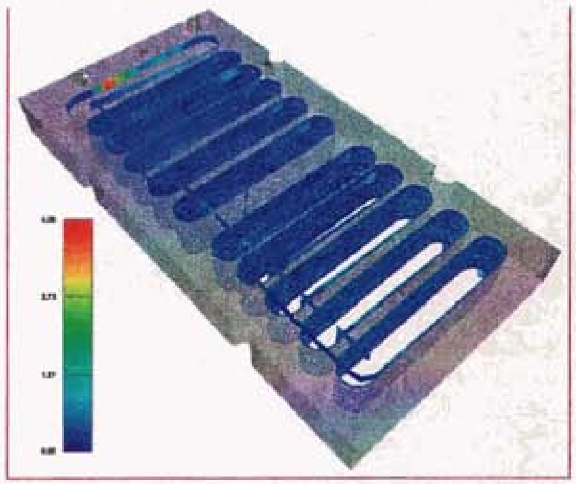

Figure 23 Slotted Part Vibration 0-100 Hz RMS

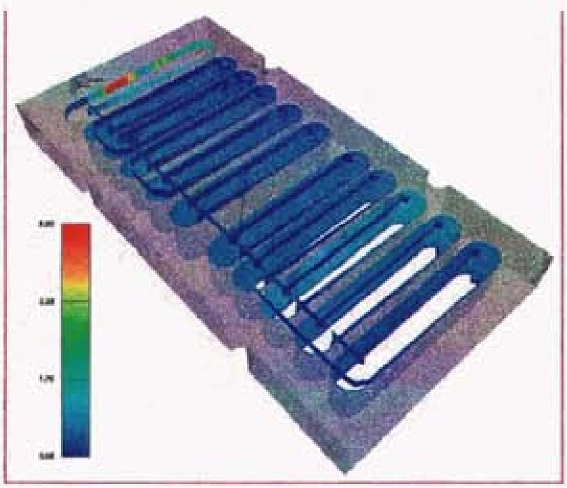

Figure 24 Slotted Part Vibration 100-600 Hz RMS

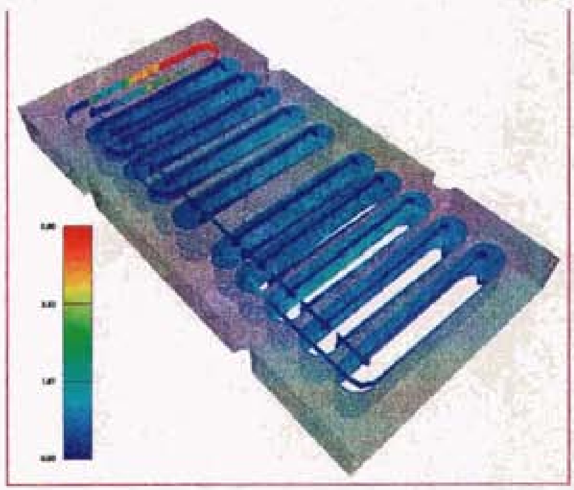

Figure 25 Slotted Part Vibration 600-3k Hz RMS

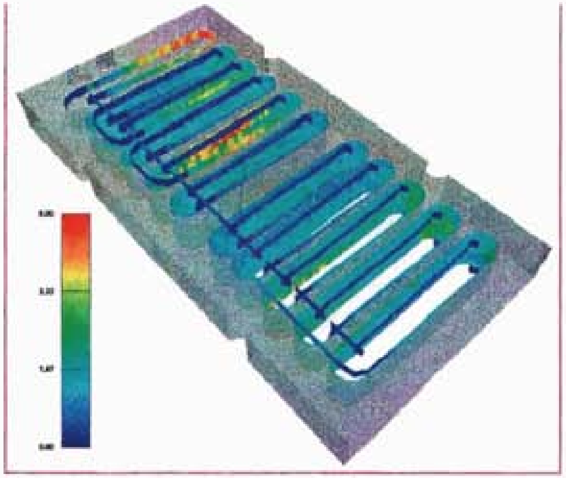

Figure 26 Slotted Part Vibration 3k-14k Hz RMS

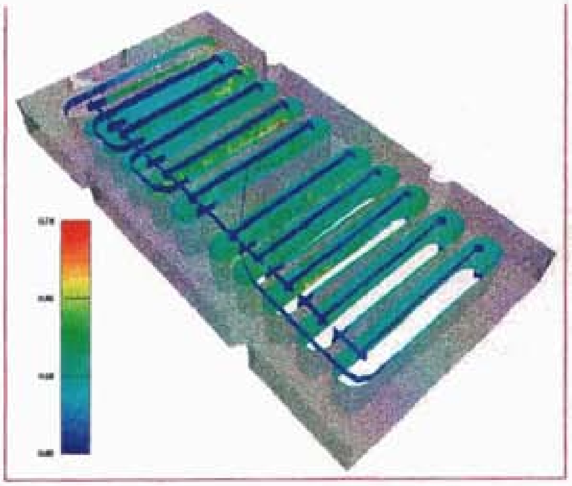

Figure 27 Slotted Part Acoustic 14k-80k Hz RMS

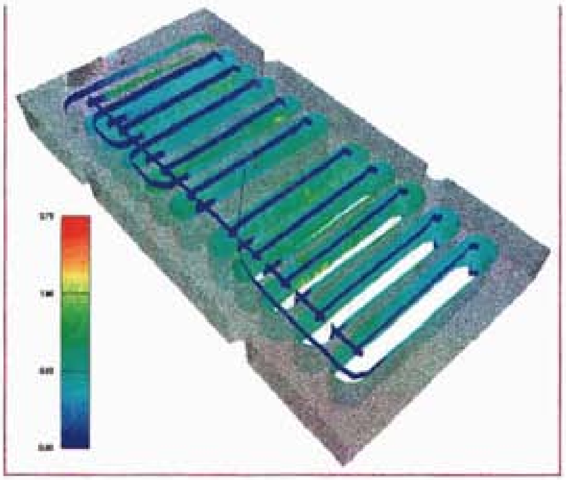

Figure 28 Slotted Part Acoustic 80k-140k Hz RMS

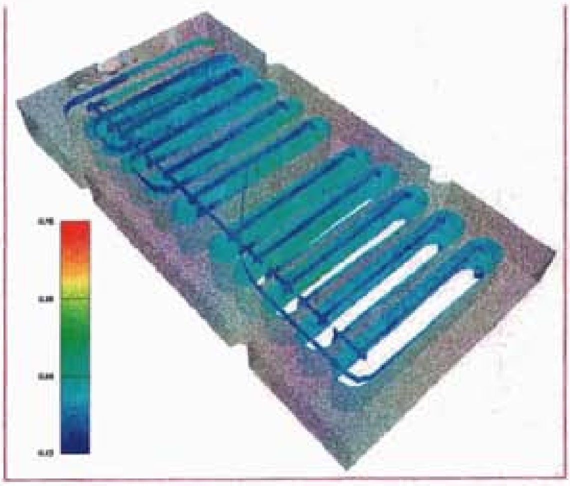

Figure 29 Slotted Part Acoustic 140k-450k Hz RMS

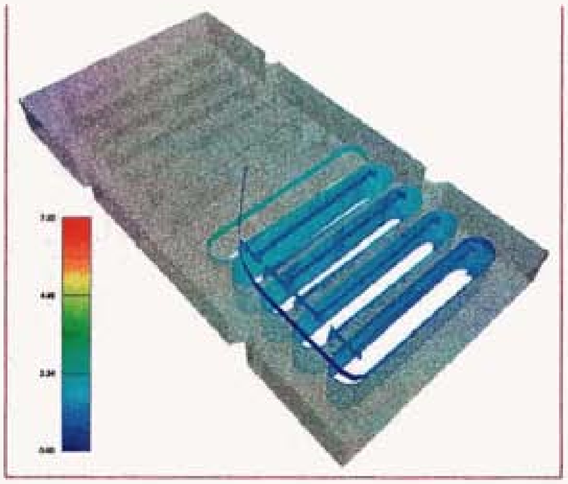

Figure 30 Slotted Part Spindle Power

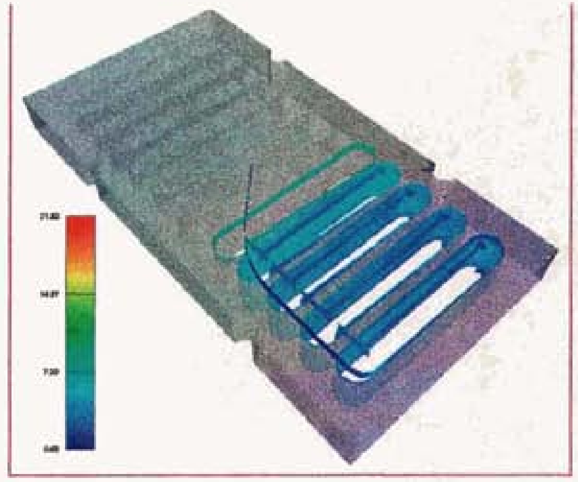

Figure 31 Slotted Part X Force

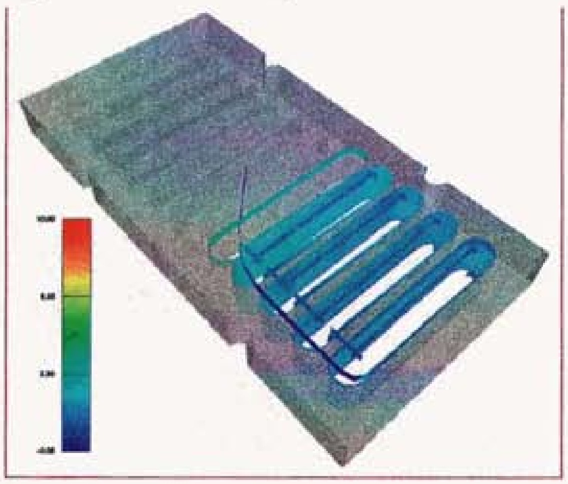

Figure 32 Slotted Part Y Force

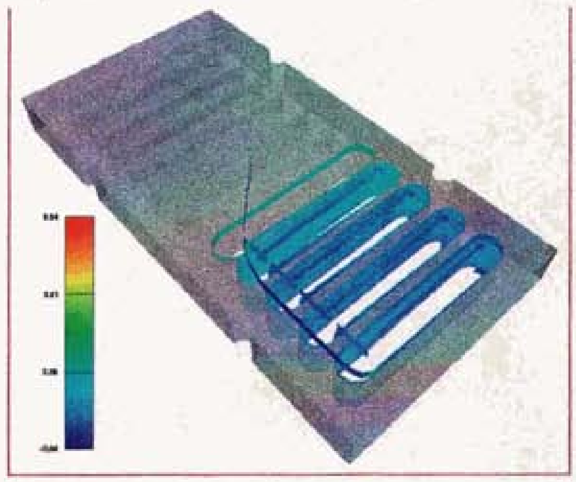

Figure 33 Slotted Part Z Force

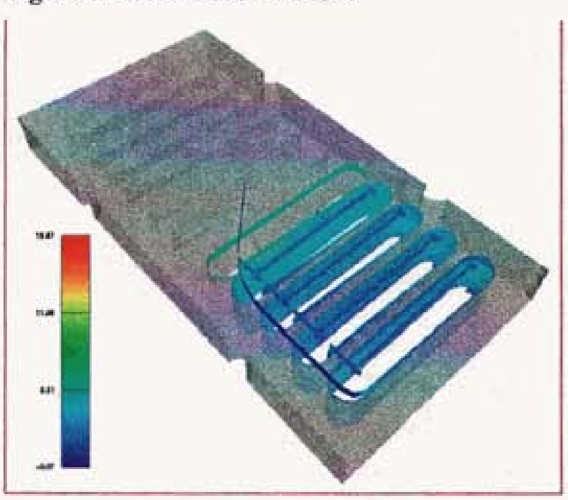

Figure 34 Slotted Part Resultant Force

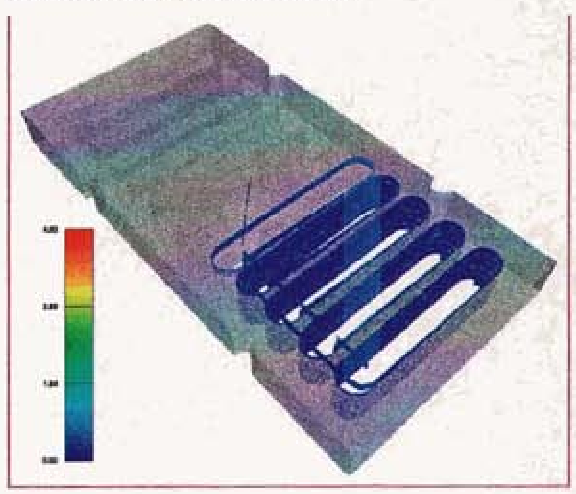

Figure 35 Slotted Part Vibration 0-100 Hz RMS

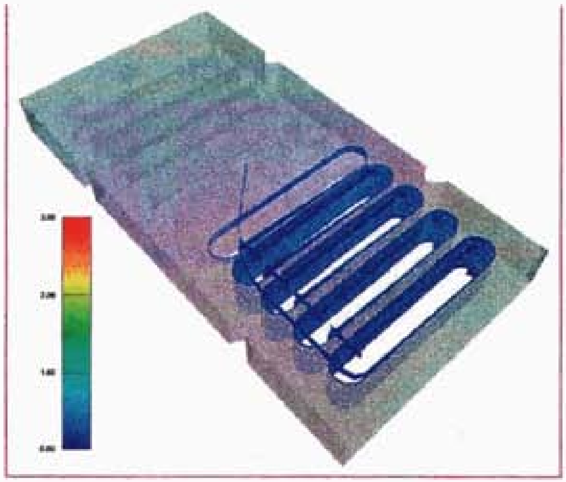

Figure 36 Slotted Part Vibration 100-600 Hz RMS

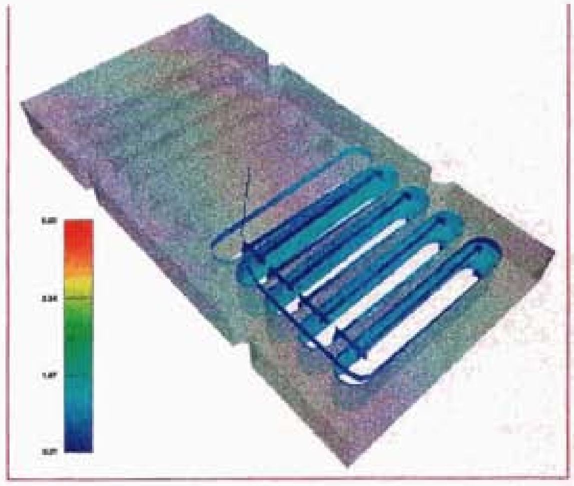

Figure 37 Slotted Part Vibration 600-3k Hz RMS

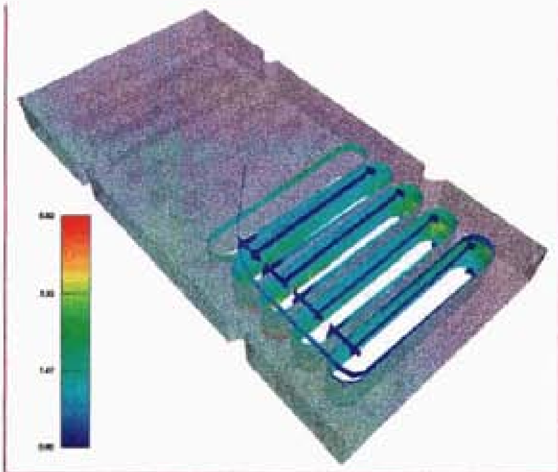

Figure 38 Slotted Part Vibration 3k-14k Hz RMS

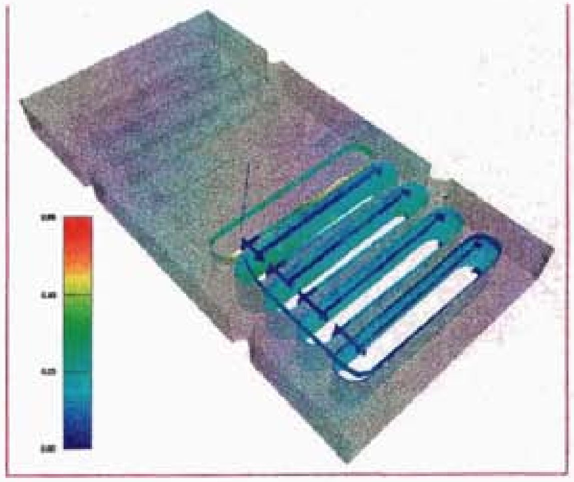

Figure 39 Slotted Part Acoustic 14k-80k Hz RMS

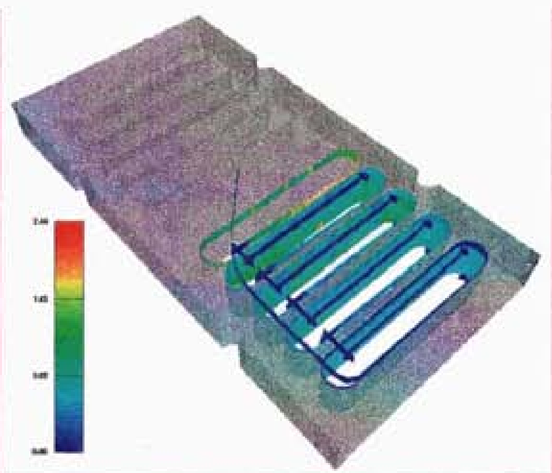

Figure 40 Slotted Part Acoustic 80k-140k Hz RMS

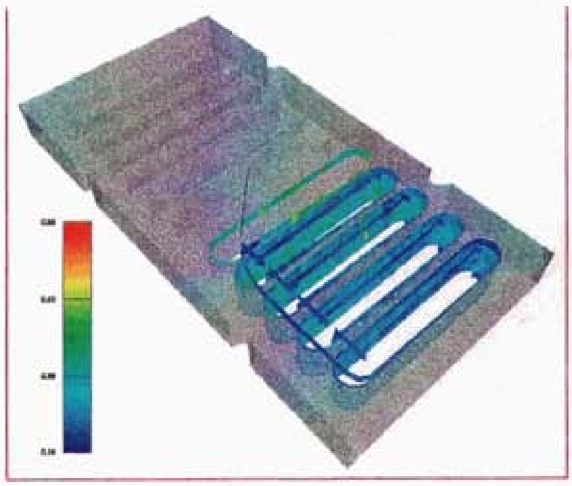

Figure 41 Slotted Part Acoustic 140k-450k Hz RMS

Figure 42 Slotted Part Close Up

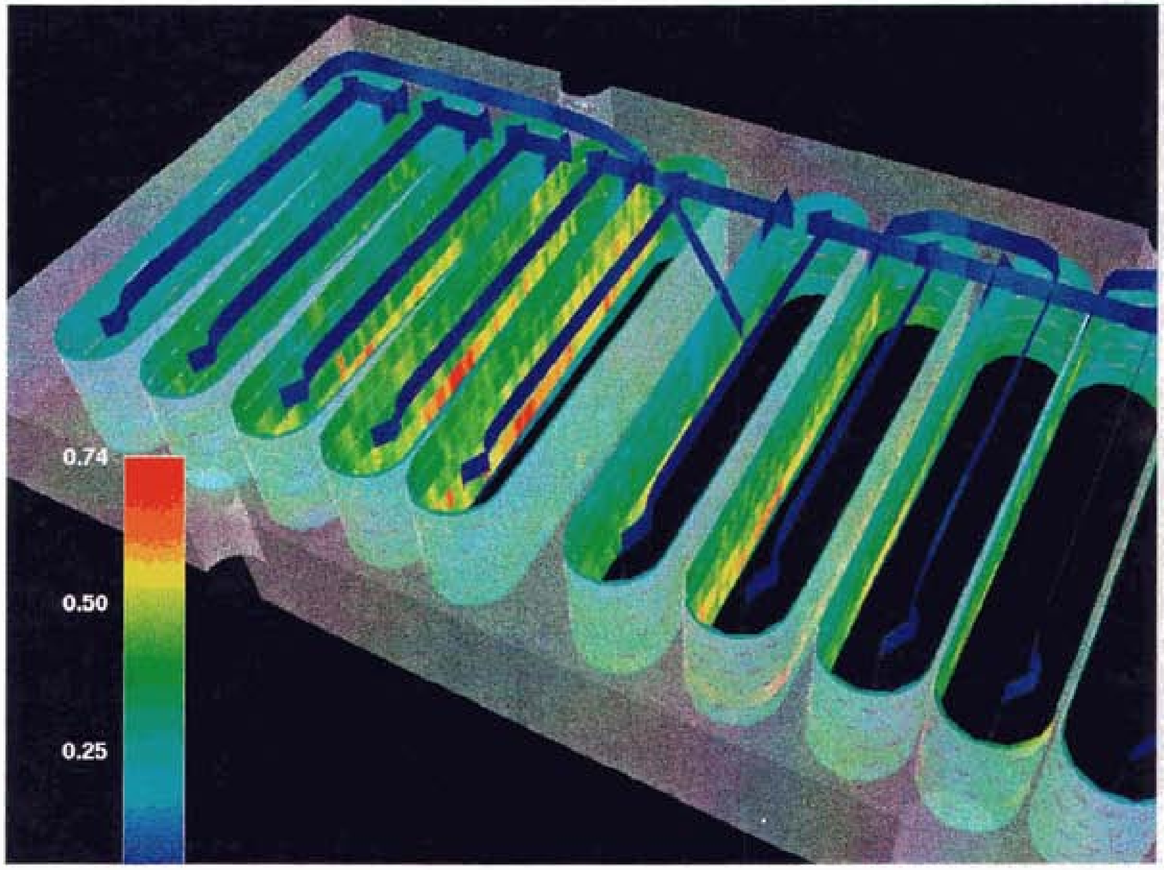

Figure 43 Slotted Part Acoustic

The force sensor for the system was inoperable for much of the time during the evaluation phase of the project. It was not sufficiently industrial hardened to handle true manufacturing environments.

The following set of output requires three different sets of figures to show all of the information because the data taken later in the process coves up data taken earlier in the process. Figure 44--Figure 51 shows the facing operation on the Circle Diamond Square part. Figure 52--Figure 59 shows the "Circle" and "Diamond" surfaces of the part. Figure 60--Figure 67 shows the "Square" surface of the part.

The part showed good surface quality for the first "Facing" operation. The data shown in Figure 44--Figure 51 shows quite a bit of oscillation, with primary transitions where the face mill enters and exits the part. Since there are not indications on the actually part of variation, we may assume that this sensor signature is acceptable for this part.

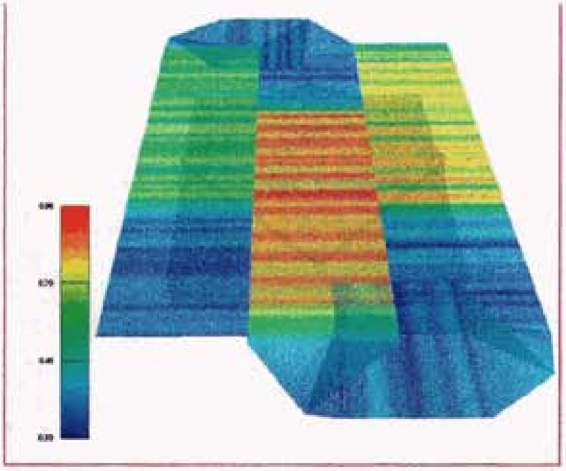

Figure 44 Circle Diamond Square Spindle Power

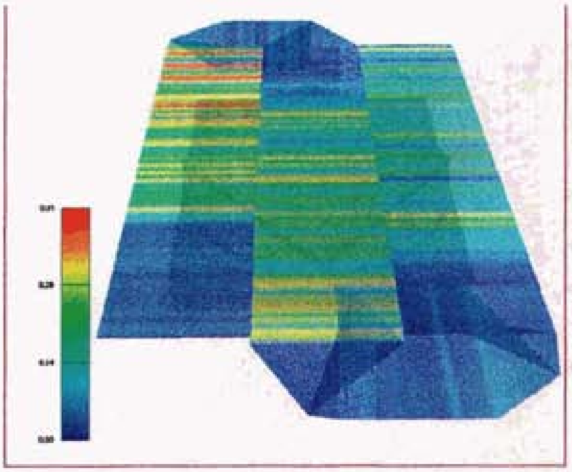

Figure 45 Circle Diamond Square Vibration 0-100 Hz RMS

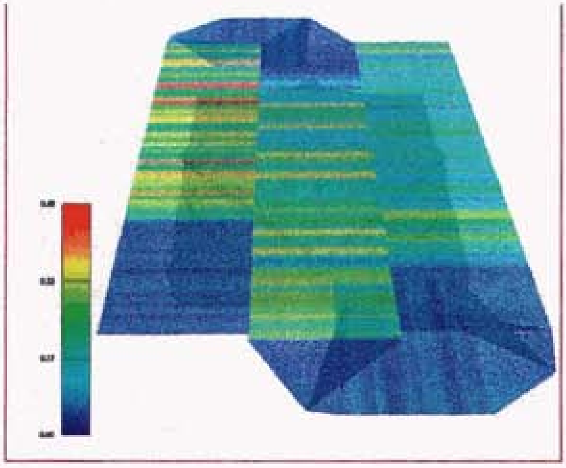

Figure 46 Circle Diamond Square Vibration 100-600 Hz RMS

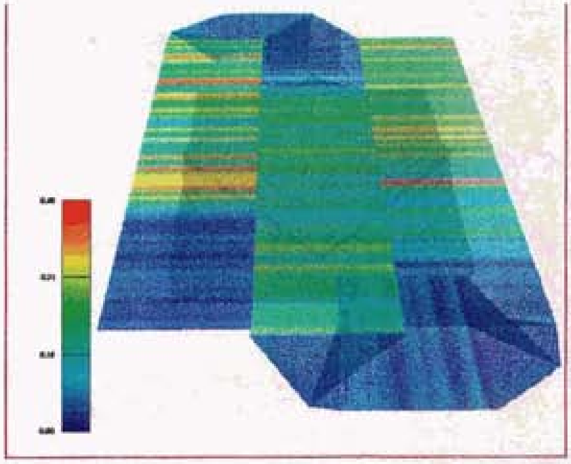

Figure 47 Circle Diamond Square Vibration 600-3k Hz RMS

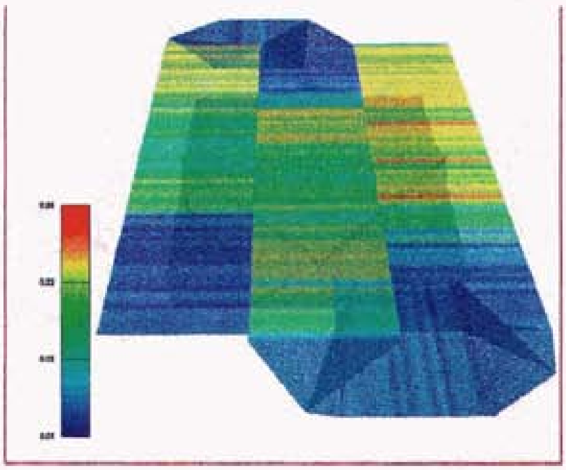

Figure 48 Circle Diamond Square Vibration 3k-14k RMS

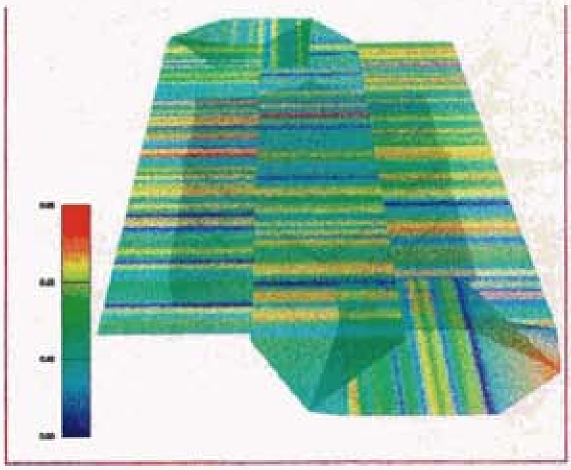

Figure 49 Circle Diamond Square Acoustic 14k-80k RMS

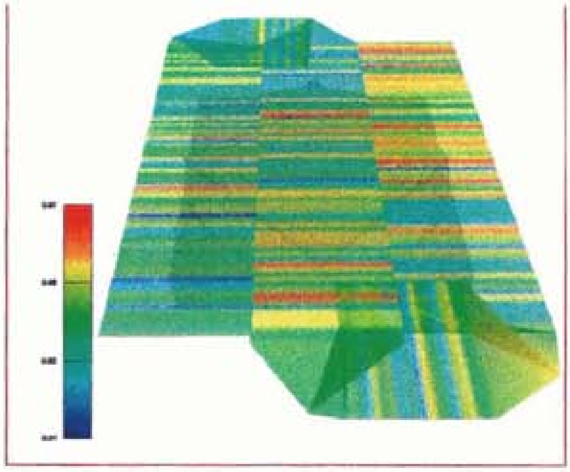

Figure 50 Circle Diamond Square Acoustic 80k-140k Hz RMS

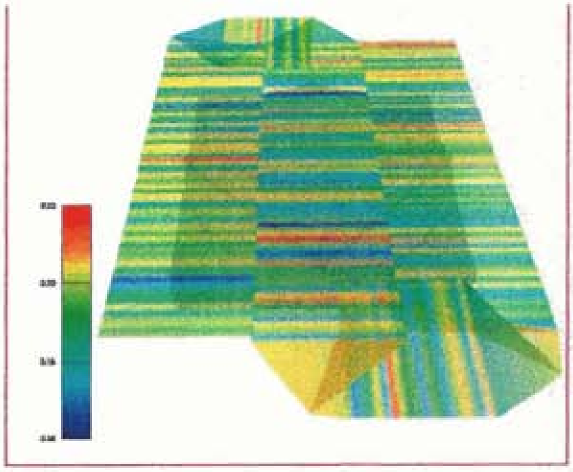

Figure 51 Circle Diamond Square Acoustic 140k-450k Hz RMS

Figure 52--Figure 59 shows the circle and diamond operations. One particularly interesting phenomenon may be noticed in Figure 54 and Figure 55. Notice that two of the opposite surfaces show intense activity, while the other two opposite surfaces show relatively low sensor activity. All four of these surfaces were anticipated to have identical cutting conditions. This phenomenon could be due to backlash in one of the axes driving the milling table. The climb milling operation could pull on the work piece, essentially working with the drive-screws in one direction, and work against the drive screws in the opposite direction.

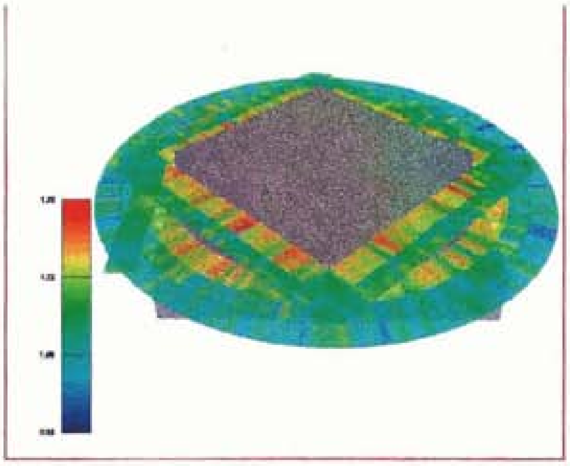

Figure 52 Circle Diamond Square Spindle Power

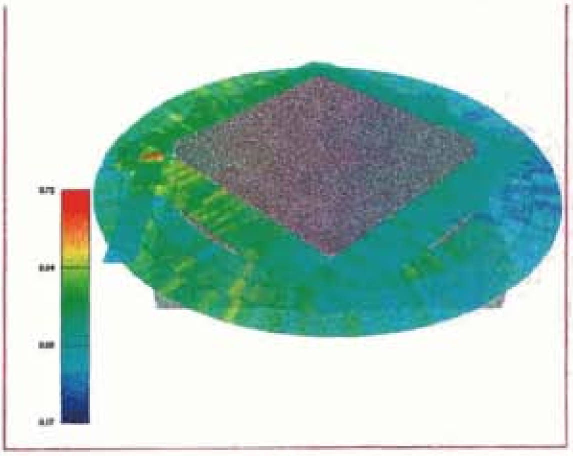

Figure 53 Circle Diamond Square Vibration 0-100 Hz RMS

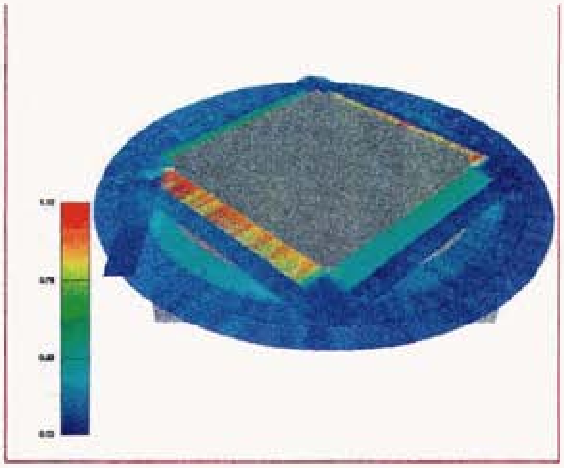

Figure 54 Circle Diamond Square Vibration 100-600 Hz RMS

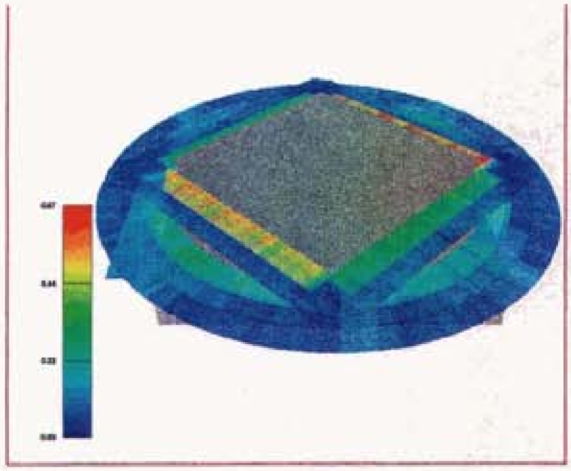

Figure 55 Circle Diamond Square Vibration 600-3k Hz RMS

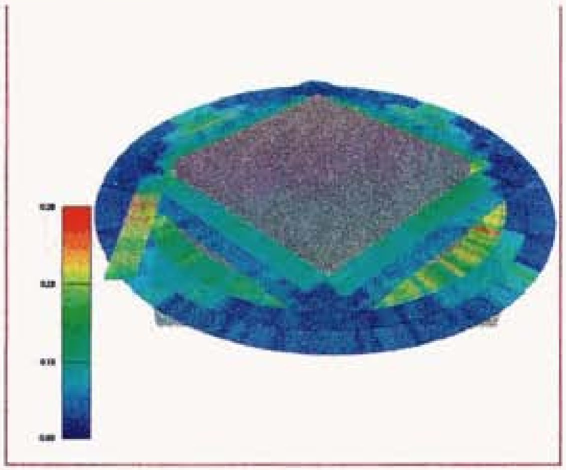

Figure 56 Circle Diamond Square Vibration 3k-14k RMS

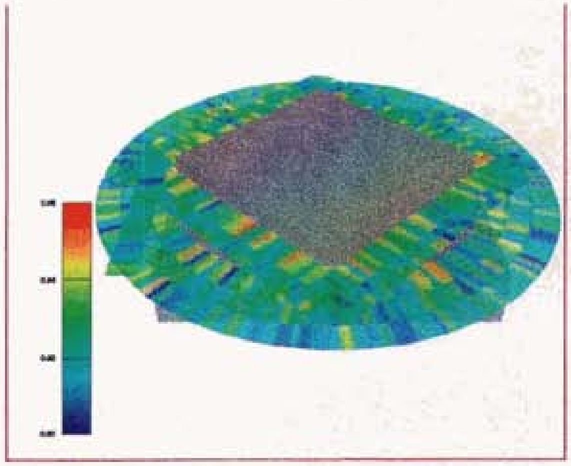

Figure 57 Circle Diamond Square Acoustic 14k-80k RMS

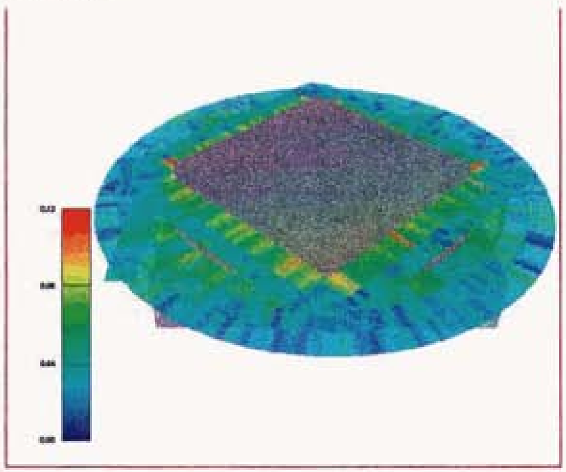

Figure 58 Circle Diamond Square Acoustic 80k-140k Hz RMS

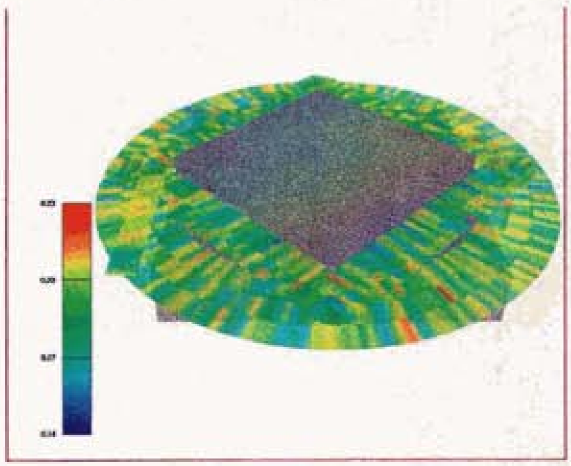

Figure 59 Circle Diamond Square Acoustic 140k-450k Hz RMS

Figure 60—Figure 67 shows the "Square" surface of the part. Two interesting phenomena occur here. First, in Figure 61, the far left and close left corners shows some activity. These two points correspond to where the part hung away from the vice it was clapped in. Second, in Figure 63, sensor activity is present on the right back edge. This corresponds to a thicker cut. Since the perimeter of the part was rough stock, it was not perfectly square or flat before machining. One noticeable bulge existed in that corner. However, no noticeable defects resulted from either of the two mentions phenomenon.

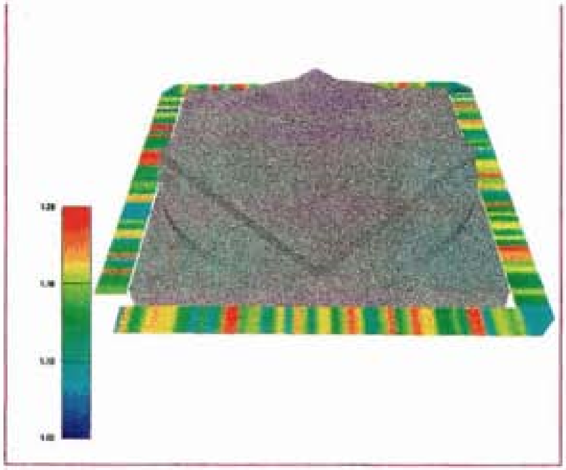

Figure 60 Circle Diamond Square Spindle Power

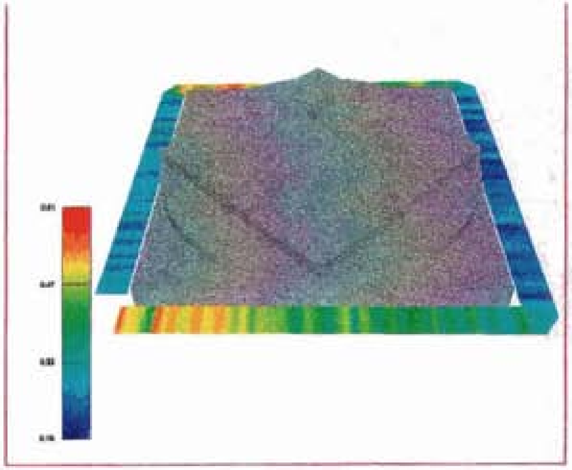

Figure 61 Circle Diamond Square Vibration 0-100 Hz RMS

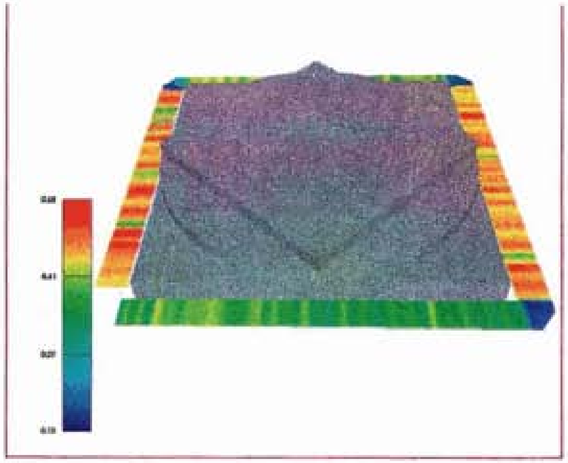

Figure 62 Circle Diamond Square Vibration 100-600 Hz RMS

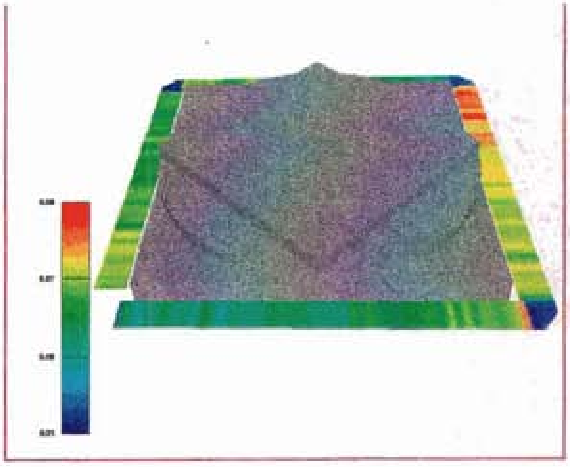

Figure 63 Circle Diamond Square Vibration 600-3k Hz RMS

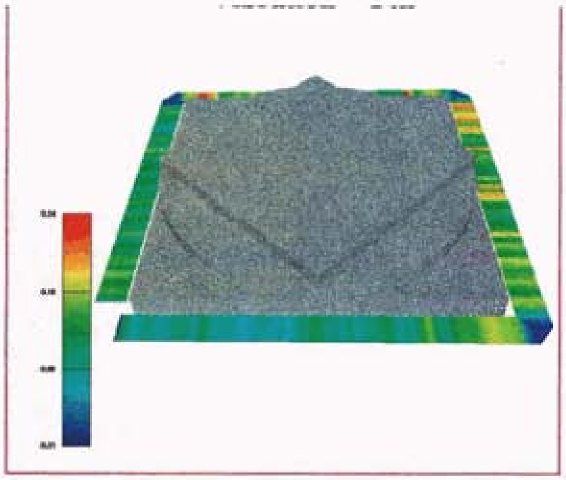

Figure 64 Circle Diamond Square Vibration 3k-14k RMS

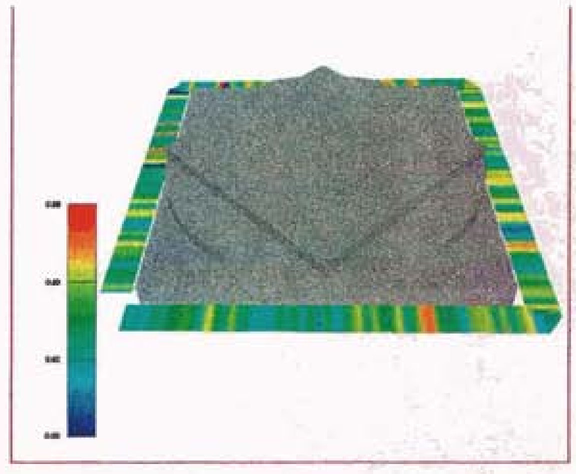

Figure 65 Circle Diamond Square Acoustic 14k-80k RMS

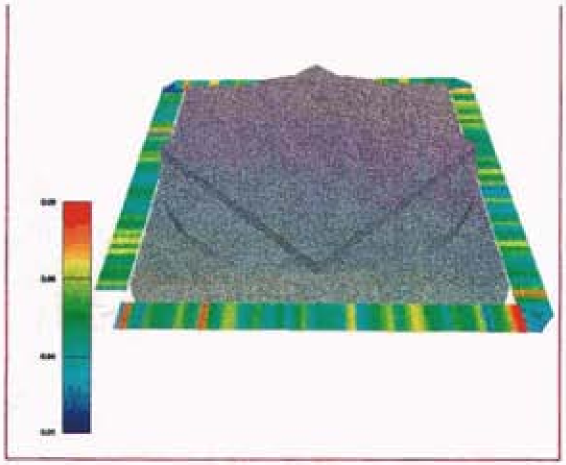

Figure 66 Circle Diamond Square Acoustic 80k-140k Hz RMS

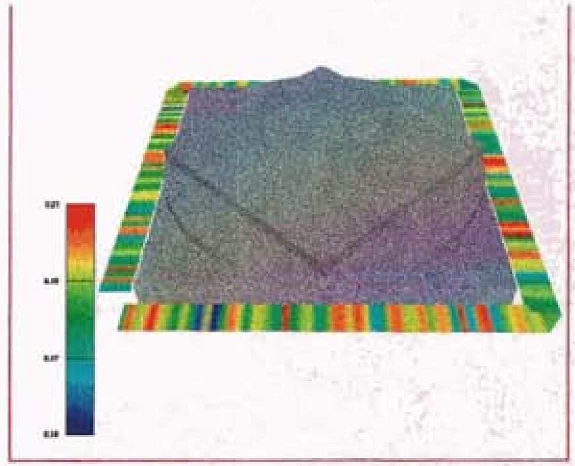

Figure 67 Circle Diamond Square Acoustic 140k-450k Hz RMS

The following two sets of output, Figure 68--Figure 83, from the Process Monitoring System shows no significant change in the process. Some of the data shows markable "oscillation" in parameters measured. Notice that the sensor reading for power fluctuates dramatically, however, the fluctuation shown represent only 4% of full scale. Since this causes confusion for the novice observer, the system may be changed in the future to show values relative to full scale. All of the EUVL parts produced were consistent and had no noticeable defects. During the finishing operations (not part of the experiment) the parts were crushed in the holding fixture and were, therefore, not fit for use.

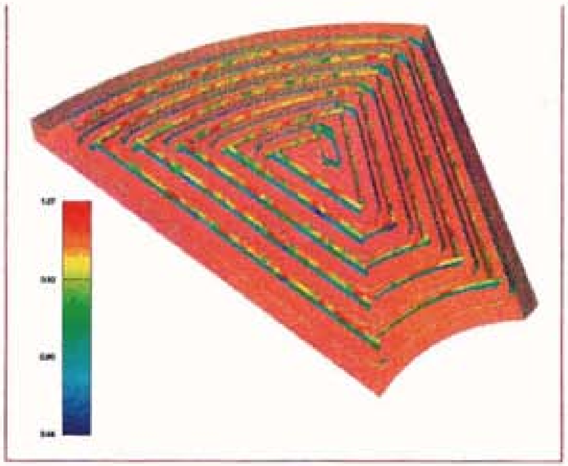

Figure 68 EUVL Part Spindle Power

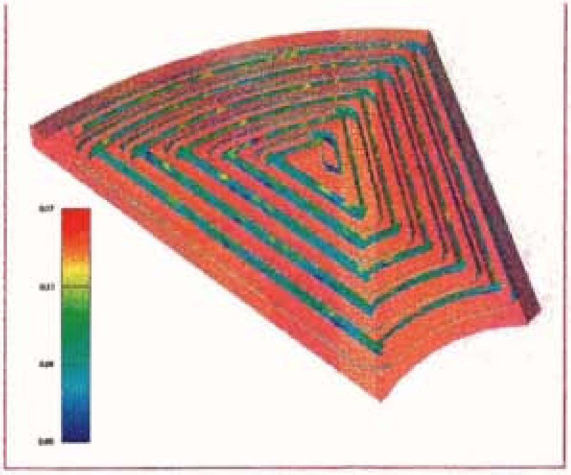

Figure 69 EUVL Part Vibration 0-100 Hz RMS

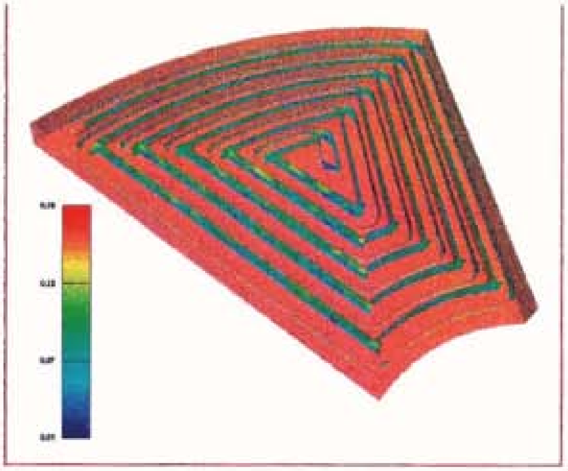

Figure 70 EUVL Part Vibration 100-600 Hz RMS

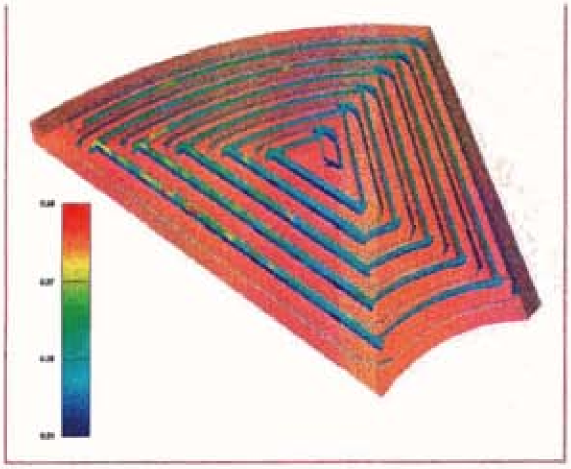

Figure 71 EUVL Part Vibration 600-3k Hz RMS

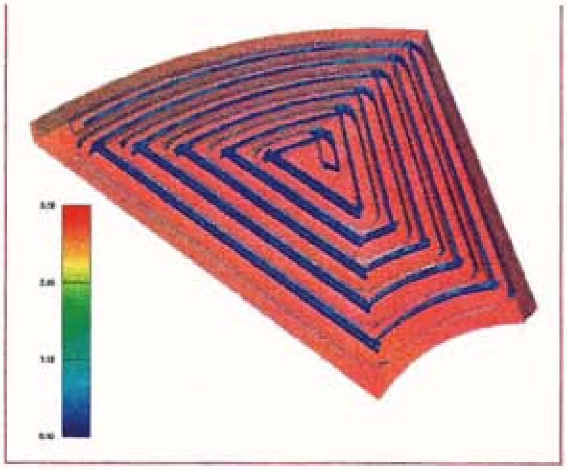

Figure 72 EUVL Part Vibration 3k-14k Hz RMS

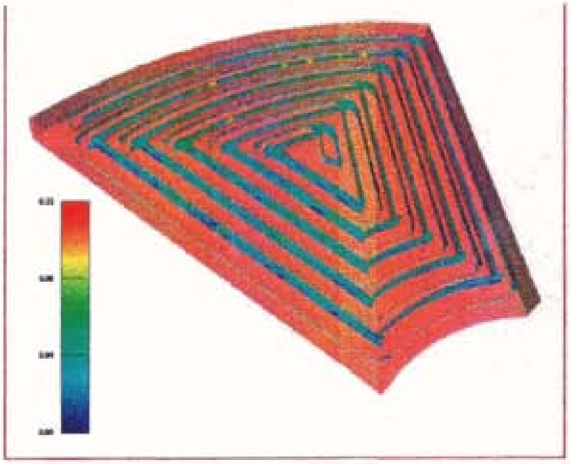

Figure 73 EUVL Part Acoustic 14k-80k Hz RMS

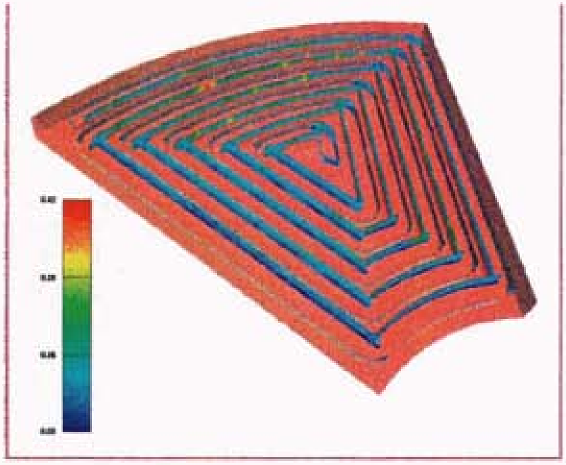

Figure 74 EUVL Part Acoustic 80k-140k Hz RMS

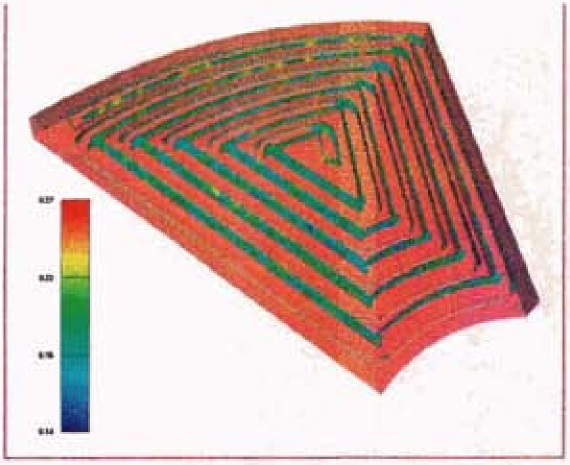

Figure 75 EUVL Part Acoustic 140k-450k Hz RMS

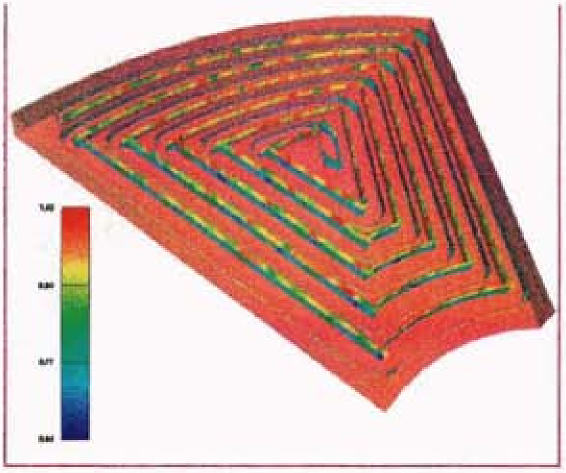

Figure 76 EUVL Part Spindle Power

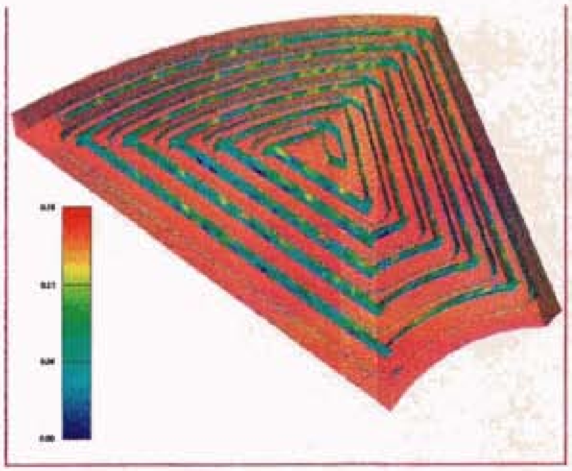

Figure 77 EUVL Part Vibration 0-100 Hz RMS

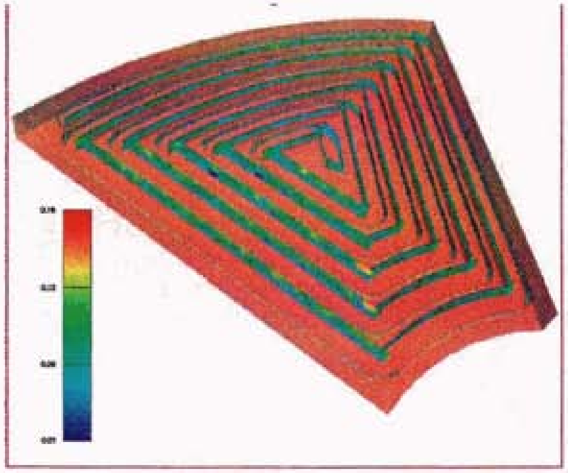

Figure 78 EUVL Part Vibration 100-600 Hz RMS

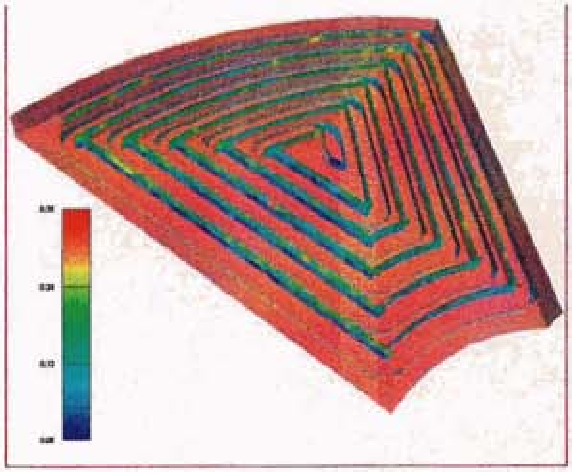

Figure 79 EUVL Part Vibration 600-3k Hz RMS

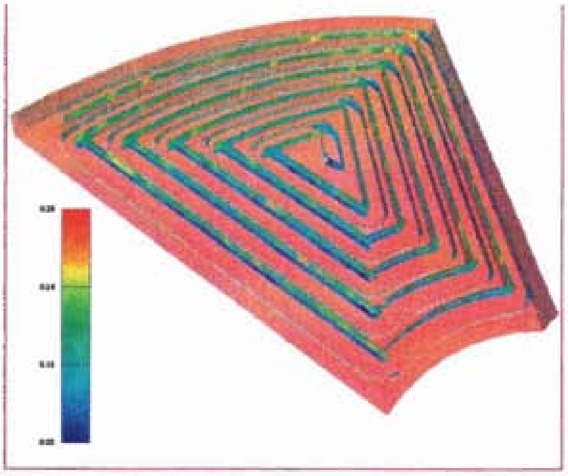

Figure 80 EUVL Part Vibration 3k-14k Hz RMS

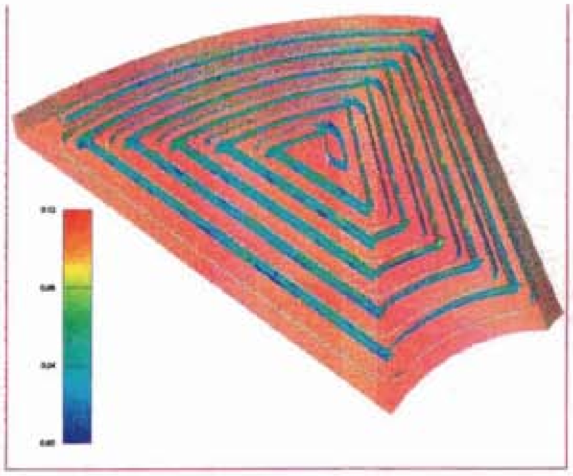

Figure 81 EUVL Part Acoustic 14k-80k Hz RMS

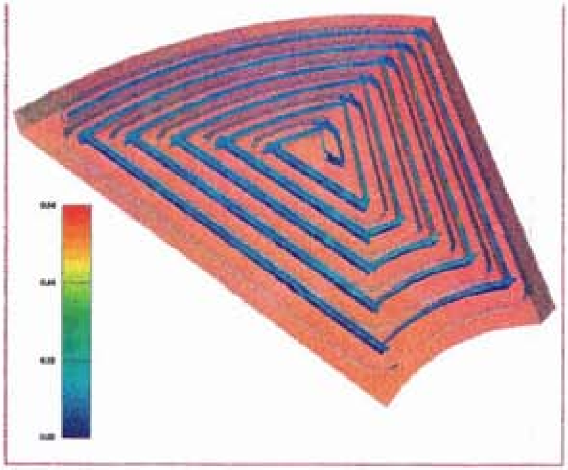

Figure 82 EUVL Part Acoustic 80k-140k Hz RMS

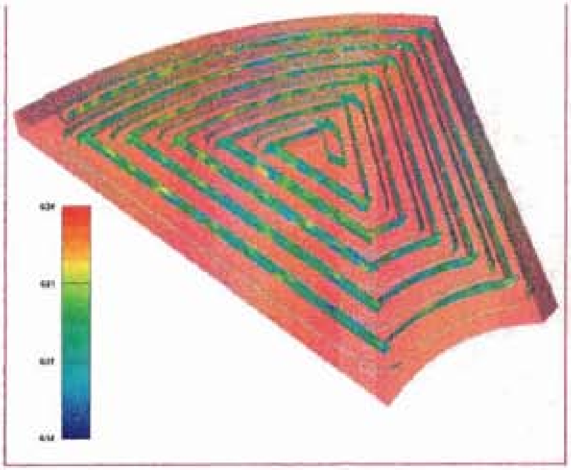

Figure 83 EUVL Part Acoustic 140k-450k Hz RMS

7. Results

The result of this research shows that process differences in the production of parts can be detected with this system. Tool breakage, chatter, and variation in machining methods (such as feeds and speeds) are readily apparent. It also shows that changes in sensor signatures can be significant before degradation of product quality. This indicates that the process monitoring system is adept in indicating production changes. Yet, it should be noted, that some of these production changes did not significantly effect part quality. Furthermore, some production problems were not detected with this system. Some EUVL parts were produced which were out of dimensional tolerance, yet no indication of change in the process was apparent from the data.

The results from these evaluation runs show that the most significant indicator of part quality was the acoustic emissions. Force and power served as a good indicator in the softer copper parts produced since the acoustic signals did not travel well through the copper. Force and power vary according more to the size of the cut being made, not the quality of the cut. However, force and power may be a good indicator of production consistency.

8. Summary and Conclusion

The focus on precision manufacturing and sensors is motivated by the desire to produce work pieces that conform to stringent tolerances of shape, form, or surface feature requirements. This is accomplished by better machine tools, better process control, and better work quality assessment. In the absence of exact models of the process, sensors are needed for feedback and state assessment. As the removal rates, contact areas, etc., become smaller and smaller, as is seen in precision machining, the sensitivity of sensors and the sophistication of the feature extraction methodologies for signal characterization become greater. It is this challenge that we are addressing with our self-tuning sensor research.

As a result of this work, we expect to be able to guarantee online quality. Any potential errors will be eliminated before they occur. In addition, because of the knowledge acquisition and process modeling based features of this system should be able to work over a wide range of manufacturing conditions for a spectrum of DP product. Process drift, material consistency, part uniformity, and tool condition will be readily detectable. Process and product improvement will be enhanced due to advanced visualization of manufacturing processes.

Researchers were amazed by the response of the machinist assigned to run the system. Simply by monitoring the output from the sensor array displayed on the process monitoring computer screen, the machinist began to develop techniques to homogenize the machining process. Once he saw how the feeds, speeds and tool paths he had chosen were quantified against cutting force, vibration, and acoustic emissions he began to think about incremental changes to make each cut more uniform. The researchers believe that once the cuts are consistent, the quality of the process can be better quantified and honed. This astounding result developed in the infancy of the project.

This system was implemented as a "Black Box" solution in that it may be placed on any machine tool without regard to the type of machine. As such, the system simply measures all inputs from the machine tool without knowing what the machine tool intends to do. This leads to inefficient data acquisition. This system will be re-implemented into the open architecture controller residing on the machine in which this system is presently placed. By implementing the system into the open architecture controller, several advantages may be made. First, with tight integration to the controller, the machine can be made to react to the sensor data in the event of a catastrophic failure. Secondly, by being integrated into the controller some information that was being measured externally, can now be accessed directly, such as position, speeds, etc. Furthermore, the controller has the capability of coordinating the input acquisition with the servo cycle, thereby improving the accuracy of the position capture information. Finally, the controller knows when the machine is supposed to be cutting and when it is not supposed to be cutting, so that a great deal of unnecessary information does not need to be gathered as it is in the black box system.

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