Y-12

Y/AMT-262

OAK RIDGE Y-12 PLANT

MARTIN MARIETTA

CRADA Final Report
for
CRADA Number Y-1291-0052

An Evaluation Of Optical Tool Inspection And Compensation Technologies

RECEIVED
DEC 19 1996
OSTI

E. F. Babelay
Lockheed Martin Energy Systems, Inc.
John Centola
Wayne Zorger
Walter Serafin
United Technologies Pratt & Whitney Division

May 15, 1994

Prepared by the
Oak Ridge Y-12 Plant
Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Systems, Inc.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Introduction

A Cooperative Research And Development Agreement (CRADA) was established April 1992 between Martin Marietta Energy Systems, Inc. (Energy Systems) and United Technologies Corporation, Pratt & Whitney Division to evaluate the existing applicability of the Energy Systems optical tool inspection and compensation system (OTICS) for use at Pratt & Whitney's East Hartford Plant. The OTICS was developed at the Oak Ridge Y-12 Plant* and optically measures the shape of a single point cutting tool. The tool shape inspection provides process information relating to tool wear and if desired the tool shape geometry can be used to generate a new numerical control machining program that is compensated for the tool forms errors.

The CRADA was planned as a multiphase project with Phase-1 being the evaluation of OTICS tool characterization capabilities at Pratt & Whitney (P&W) utilizing their materials and machining operations. Phase-2 of the project will be defined to focus on the development of a second prototype system that encompasses the technologies assessed in Phase-1 and achieves an improvement in accuracy and speed of inspection. The primary focus of the Phase-1 assessment included both the tool measurement capability and an evaluation of tool wear characteristics observed in machining tests. Tool inspection accuracy becomes an issue in Phase-1 as the cutting tools to be evaluated at P&W are much larger in size than those measured at Y-12 with OTICS. Due to the fixed measurement resolution of OTICS, an increase in the tool size to be inspected will result in a direct decrease in the inspection resolution. One of objectives of the Phase-1 tests was to determine if the decreased inspection resolution of larger tools will hinder the use of the OTICS technology. A second objective of Phase-1 testing was a demonstration of the varied technologies required to compensate the tool path for tool form errors.

The OTICS technology was developed at Y-12 for the precision flexible manufacturing systems (PFMS) project. One of the overall goals of the PFMS project was development of technologies to allow the manufacture of single point turned parts with a contour accuracy of +/- 0.0005 inch. Process analysis tests performed for the PFMS project identified tool geometry errors to be a significant component of the total part contour error. The OTICS vision sensor was initially developed as a non-contact tool set gage. However, after its capacity to accurate measure the cutter tool form was established, software was developed to compensate the numerical control (NC) tool path for the tool geometry errors reported by the OTICS gage. A production version of the OTICS technology has been integrated by Moore Special Tool Inc. into an enhancement upgrade of a Excello T-base lathe. The enhanced T-base lathe package includes the necessary system software that will use special G-codes in the part program to automatically initiate the tool inspection and the tool path compensation of the final cut.

The Phase-1 evaluation of optical tool inspection technologies at P&W was designed as a series of machining tests. These tests simulated a finish cut sequence utilized in the manufacturing of a specific class of turbine engine parts. The test part geometry, material and cutting tools were chosen to represent the typical manufacturing process in use at P&W. While the evaluation testing of OTICS was not performed on actual production parts, information gained from the machining tests would indicate what benefits could be realized form the incorporation of optical tool inspection technologies into the production turning process at P&W.

* Managed by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy under contract DE-AC05-840R21400.

System Description

The principal hardware components of the optical tool inspection system are an IBM 7562 Industrial Computer with a Data Translation DT-2953 video interface board and a Plunix remote head CCD video camera with a RS-170 interface. The video camera is mounted at a location on the lathe where the slides can move the tool into the camera's field-of-view. A diffuse light source, which is supplied by fiber optics, is mounted in-line with the camera and serves as a back-light when the tool is being inspected. A microscope objective lens and extension tubes are utilized to provide the desired magnification of the tool. This optical system provides a shadow image of the tool to the video camera with the tool "cutting" the light with the same geometric form that will cut the part. Figure 1 shows the camera, light source and a 0.125 inch radius tool mounted on the Sunstrand slant-bed lathe that was used for the Phase-1 tests.

The OTICS software which executes on the IBM-PC begins each tool inspection by capturing a single video frame with the frame-grabber card. Figure 2 represents a typical video image of a 0.046 inch radius tool. With the camera focused at the cutting plane of the tool, the shadow image provides an accurate geometric representation of the cutter form. To determine the shape of the cutting tool, the inspection software analyzes the light-dark transition of the captured video image. A smaller region-of-interest is examined along both columns and rows of the video data to detect edge points of the tool. A schematic representation of this scanning process is shown in figure 3. Once the edge points are determined, additional software algorithms construct a dimensional

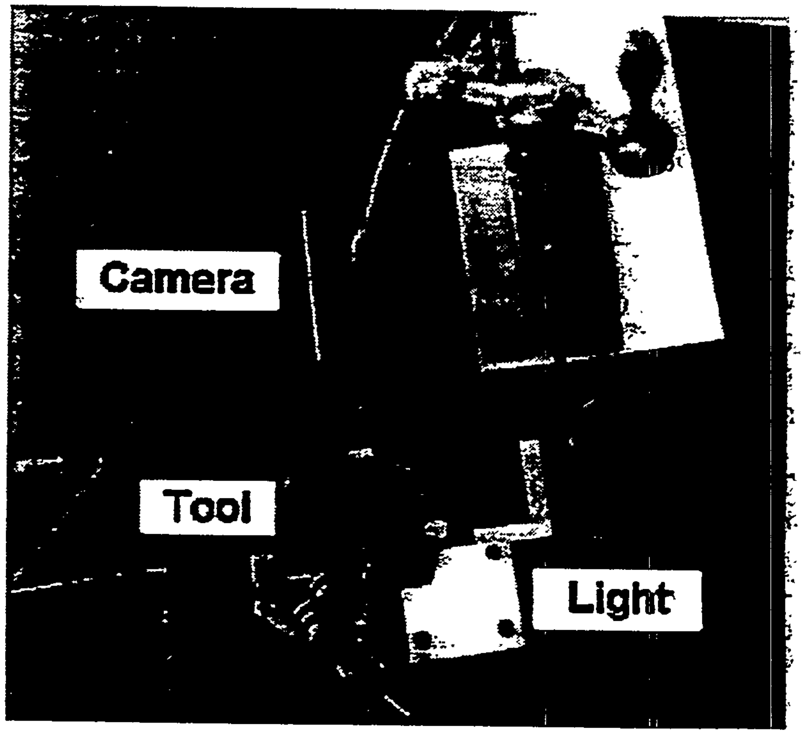

Figure 1. OTICS mounted on slant-bed lathe.

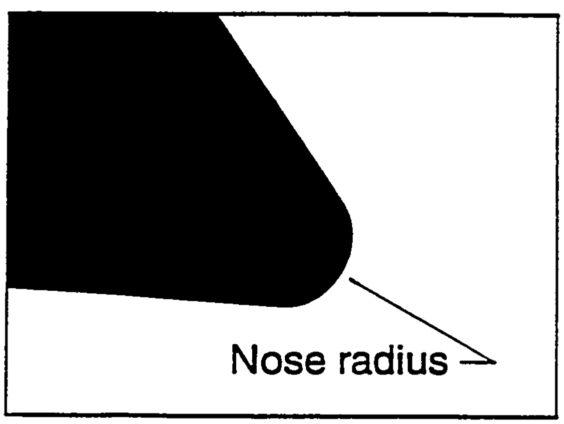

Figure 2. Video image of tool.

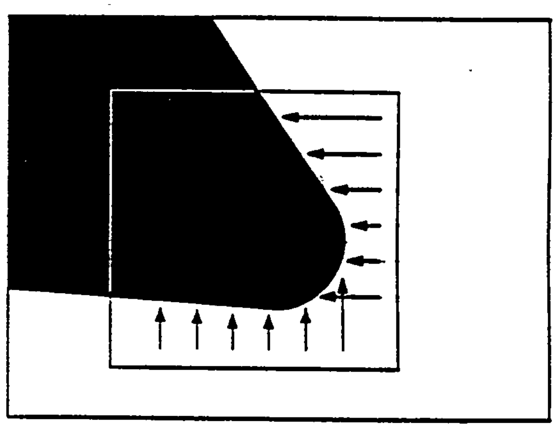
Figure 3. Detecting edge points in two directions.

inspection of the tool. Two types of dimensional inspections were calculated for the Phase-1 tests. The first type allowed sequential inspections of the tool to be compared to an initial inspection of a new tool. This inspection highlights absolute changes in the cutter shape and thus indicates tool wear. The second type of inspection determined the deviations of the tool form compared to the theoretical 0.125 in. radius tool which was assumed for the generation of the NC program.

A Sunstrand 400C slantbed lathe was selected for the test bed and the OTICS camera, shown in figure 1, was mounted on the Z-axis slide on the end opposite to the lathe spindle. A test part which was designed to model the part geometry shown in figure 4 was fabricated from 8% machinable nickel. The machining of the inner contours of the test part required two different cutters. The first, P&W designation CM250-95, was a 50 degree diamond shape tungsten carbide insert with a 0.046 inch nose radius. The second cutter, P&W designation CM417-3, was a single end "V" bottom tungsten carbide insert with a 0.125 inch radius, 200 degree included angle, button shape profile. The full radius of the cutter being wider than the holding shank gives this insert the appearance of its common shop name of a "dog bone" tool. Figure 4 also illustrates the contour features of the test part that were machined with the two cutters.

Tool Wear Measurement Evaluation

The first on-machine evaluation of OTICS was designed to measure the tool wear patterns that result from the single-point machining process in use at P&W. The detection of tool wear establishes a basis for the applicability of optical tool inspection techniques to the machining process as it provides a benchmark of the tool inspection capability. In addition, evaluating the tool wear data provides further insight into the machining process, such as the magnitude of wear and the stability of the cutter form during the final cut. Obviously, if

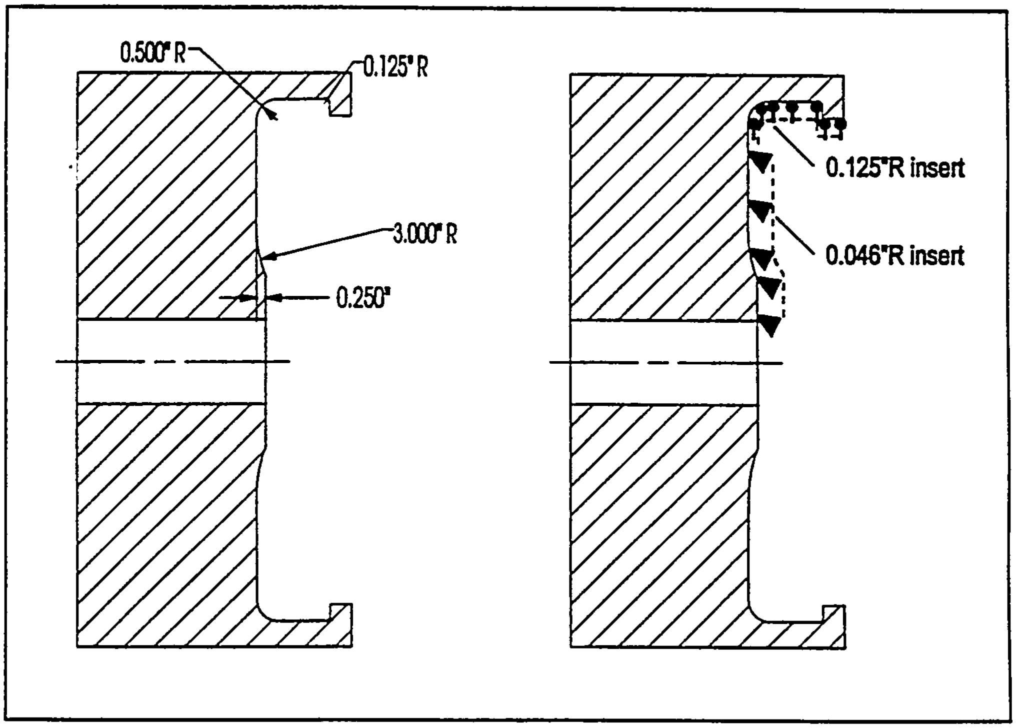

Figure 4. Test part configuration and tool paths used for wear experiment.

the magnitude of tool wear is insignificant to other variables of the process error budget, the value of optical tool inspection is minimal. Likewise, if the goal is to use tool inspection data to compensate the NC cutter path for tool form errors, the compensation process accounts only for the tool errors present before the finish cut and any subsequent tool wear will limit the compensation benefit.

The experimental procedure used for the tool wear machining tests started with an initial OTICS inspection of two new cutter inserts once they had been installed in the lathe. The appropriate NC tape sequence was begun and a single machining pass was completed with each insert. After each machining sequence was complete the inserts were re-inspected with the OTICS system. For the tool wear tests, data was collected for a total of twelve machining sequences using six pairs of inserts. Most inserts were used twice, while one pair was used for three cuts and another pair received only one cut. As noted in table 1, various machining parameters were utilized to evaluate the capability of the OTICS setup to measure tool wear.

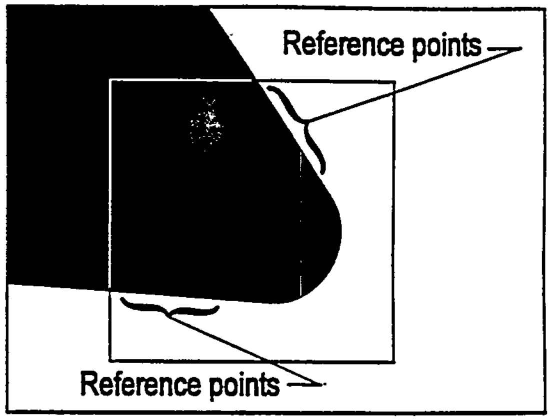

Figure 5. Regions of tool used for center reference.

The OTICS software was modified to perform the tool wear calculations required for the Phase-1 tests. Before the modifications, the OTICS system reported the tool form as deviations from a nominal tool radius whose center was located from points on the tool that are tangent to the lathe's slide motion. Since with this type of inspection the center is located from points on the tool that are subject to wear, any absolute or cumulative tool wear is not measured. To track absolute wear, the OTICS software was modified to located the inspection center relative to regions that would not be subject to wear. Figure 5 indicates the regions of the .046 inch radius tool that were used for the center reference and similar regions were used on the .125 in. radius tool. This type of evaluation readily allows the comparison of a series of inspections of a single tool and will track absolute changes in the tool shape caused by tool wear.

The inspection data was stored as a series of files on the IBM-PC. The OTICS software has the capability to overlay a series of inspections for a single insert and graphically plot deviations of the shape, which is the tool wear. Figures 6 and 7 show the results of the tool inspections collected for the tool wear tests. Each plot shows the basic cutter profile (the outer, smooth curve) and is created from the initial inspection of the insert. A second curve is plotted parallel to the first inspection and provides a reference for the magnification applied to all other inspections. A scale factor was selected to establish a 0.002 inch reference which is identified in the inspection plots. Tool shape deviations for each of the subsequent inspections of an insert are overlaid in the plots and the regions of the tool receiving the greatest wear are easily identified.

The OTICS system optical field-of-view was also increased for the inspection of the P&W tools. The larger tools to be inspected for Phase-1 made it necessary to change the optical magnification to image a 0.250 inch square region. Since the OTICS measurement resolution is approximately +/- 1/2500 of the field-of-view, the resolution obtained for the Phase-1 tests was +/- 0.0001 inch and was verified with on-machine testing when the OTICS system was installed at P&W. This resolution, which is approximately five times larger than

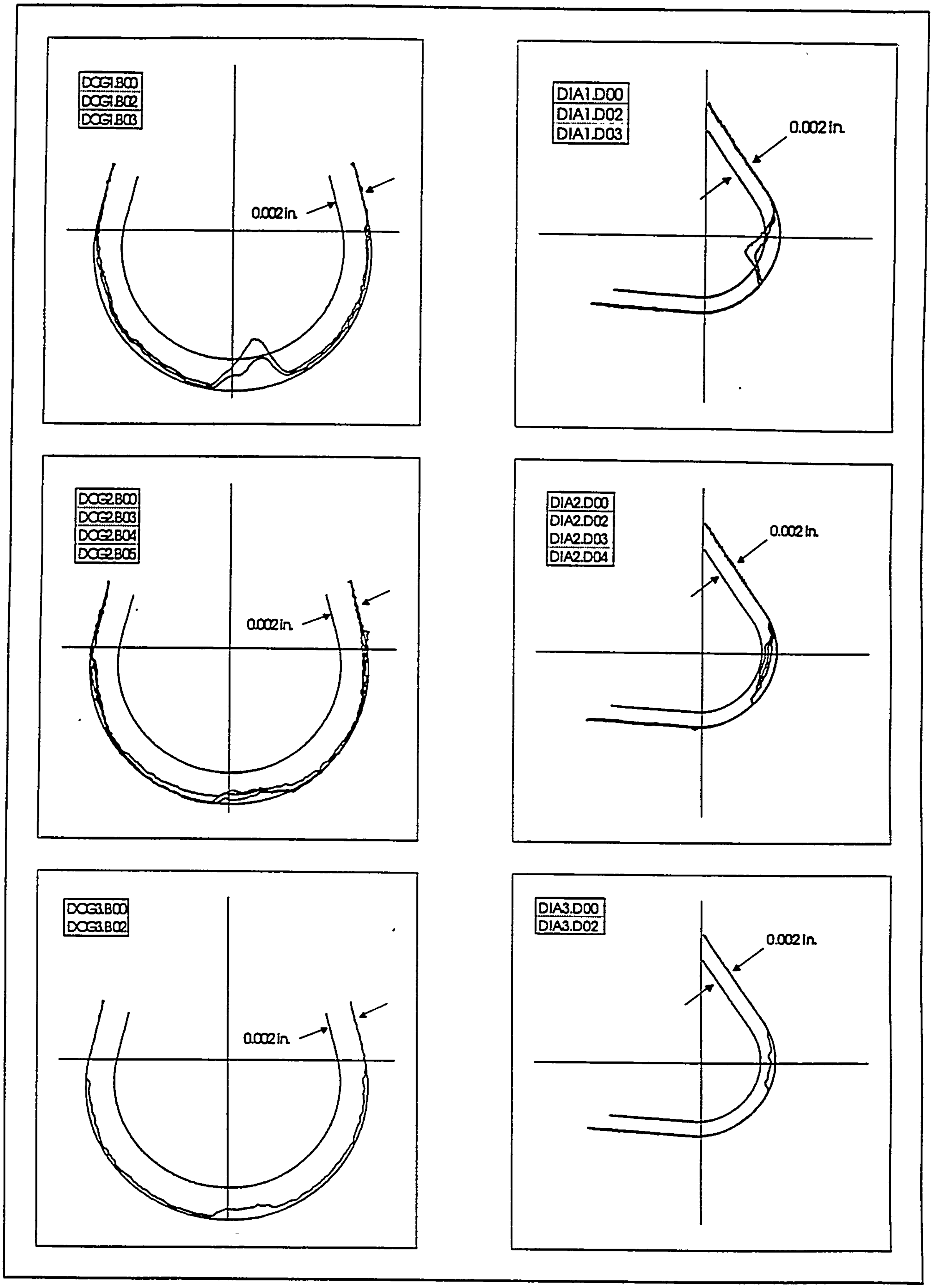

Figure 6. Tool profiles measured during wear experiment.

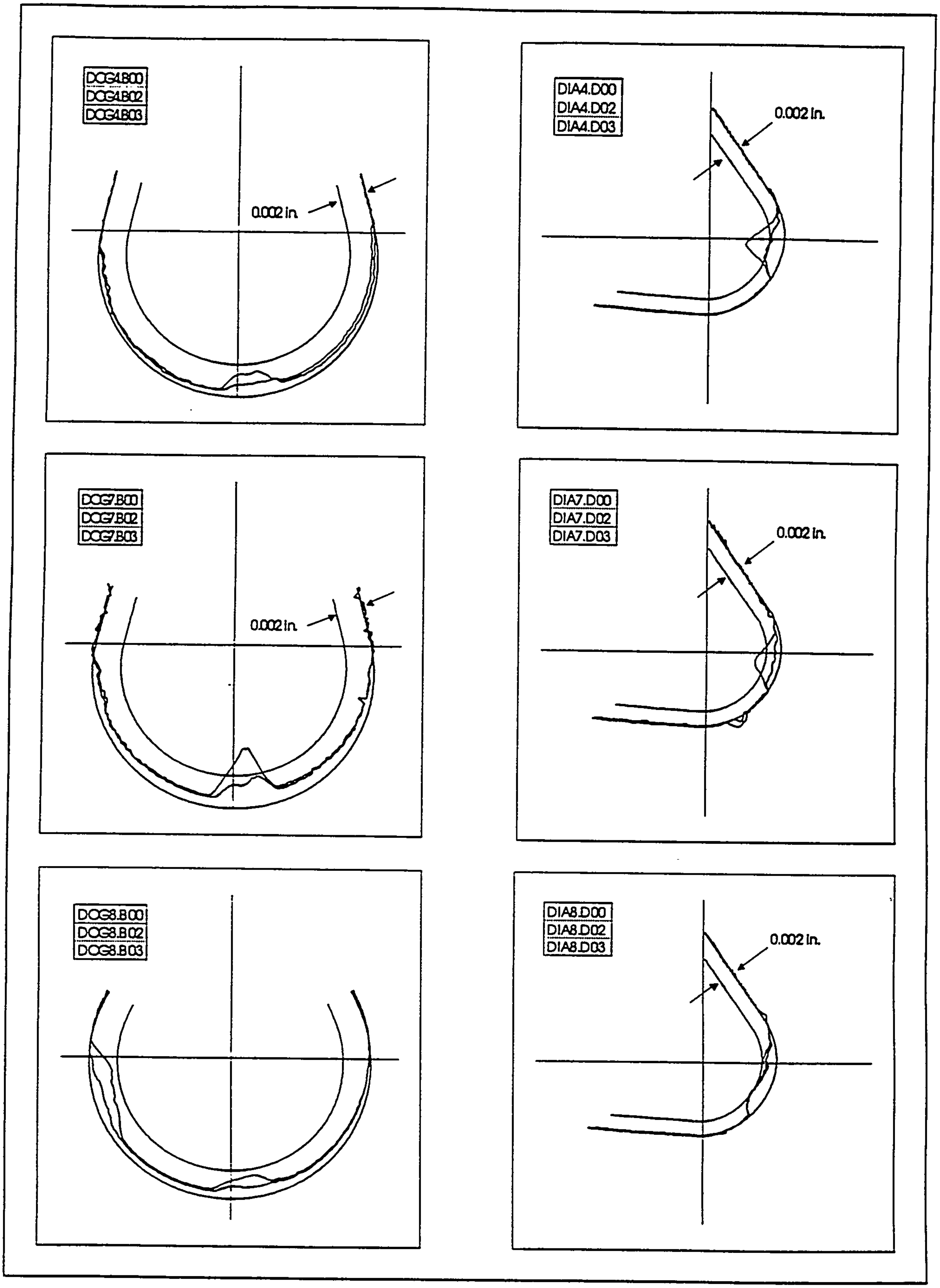

Figure 7. Tool profiles measured during wear experiment.

Tool ID	Cut #	File Name	Total Wear (mil = 0.001 in.)	Incre. Wear (mil)	Surface Speed (SFM)	Feed Rate (IPR)	Depth of Cut (in.)
DIA1	1	DIA1.D02	2.6	2.6	153	.005	.010
DIA1	2	DIA1.D03	4.0	1.4	114	.010	.010
DIA2	1	DIA2.D02	0.9	0.9	100	.012	.010
DIA2	2	DIA2.D03	1.3	0.4	105	.007	.010
DIA2	3	DIA2.D04	1.7	0.4	114	.008	.005
DIA3	1	DIA3.D02	0.8	0.8	114	.010	.005
DIA4	1	DIA4.D02	2.2	2.2	153	.005	.005
DIA4	2	DIA4.D03	5.0	2.8	153	.005	.005
DIA7	1	DIA7.D02	0.9	0.9	114	.008	.005
DIA7	2	DIA7.D03	3.3	2.4	153	.005	.005
DIA8	1	DIA8.D02	1.9	1.9	150	.005	.010
DIA8	2	DIA8.D03	2.0	0.1	114	.005	.010
DOG1	1	DOG1.B02	2.1	2.1	153	.005	.010
DOG1	2	DOG1.B03	3.5	1.5	153	.010	.010
DOG2	1	DOG2.B03	0.8	0.8	100	.012	.010
DOG2	2	DOG2.B04	0.6	-0.2	110	.012	.010
DOG2	3	DOG2.B05	0.9	0.3	114	.005	.005
DOG3	1	DOG3.B02	0.8	0.8	114	.010	.005
DOG4	1	DOG4.B02	1.0	1.0	114	.008	.005
DOG4	2	DOG4.B03	1.8	0.8	153	.005	.005
DOG7	1	DOG7.B02	2.2	2.2	153	.005	.005
DOG7	2	DOG7.B03	4.2	2.0	153	.005	.005
DOG8	1	DOG8.B02	2.3	2.3	153	.005	.010
DOG8	2	DOG8.B03	4.0	1.7	153	.005	.010

Table 1. Initial OTICS test results.

the resolution obtained for the inspection of the smaller tools at Y-12, is an underlying performance measure and should be considered when analyzing the inspection information obtained in the Phase-1 tests.

To assist in the estimation of the tool wear, an enhancement was added to the OTICS software which searched the tool shape deviations to locate the position of greatest wear. Once the location of maximum wear was determined, the software calculated an average tool wear value over a five degree region. Because the tool wear is calculated relative to the first (reference) inspection, a second parameter was calculated from the difference in wear for successive machining passes of a given tool. This differential wear provides some indication of the amount of additional wear that results from the second use of the tool. As noted earlier, the greatest benefit of tool path compensation is obtained when the insert has a small amount of additional wear during the finish cut. A summary of the tool wear numbers along with the machining parameters (depth of cut, surface speed, and feed rate) for each cut are reported in Table 1.

Tool Path Compensation Demonstration

The second on-machine test completed during Phase-1 was a demonstration of the tool path compensation technology of OTICS. Because scheduling constraints precluded completing a series of machining evaluations, this test was performed to show the fundamental operations of the OTICS tool path compensation process. As discussed earlier, the compensation process starts with an optical inspection of the cutter which produces a dimensional inspection of the actual cutter shape. The actual tool shape is compared to the theoretically perfect cutter assumed by the NC part program and results in a list of tool shape errors. The inspection results are then supplied as input to a second computer program which reads the original part program and produces a new program which is compensated on a block-by-block basis for the cutter shape errors.

The OTICS compensation software algorithms were designed with a some basic assumptions in the compensation process. These conditions are important to consider when implementing the technology and were included in the planning of the compensation demonstration experiment at P&W. First, the OTICS compensation process only corrects the part program for contour errors due to tool shape errors. Specifically, any program blocks that move parallel to the lathe's X or Z axis would not be affected because the dimensional inspection of the cutter is referenced to these directions and by definition there are no tool shape errors associated with these motions. Thus the compensation process strives to produce the correct shape of a contour which is cut with machine motions that are not parallel to the machine axis. Additionally, the location of the contour in the part is controlled by applying simple X - Z offsets within the NC control. Finally, the OTICS compensation process requires a NC program created with linear interpolation and at present can only correct a workpiece contour segment of up to 90 degrees.

To satisfy the design requirements of the OTICS compensation process, the tool wear test part was re-machined to provide two 90 degree inside radius contours. A part program was created to machine the 0.5 inch radius contours using a 0.125 radius dog bone insert. The test part also included straight sections (facing and inner diameter) on each end of the contours. These straight sections provided datum surfaces for a coordinate measurment machine (CMM) to locate the center of the contour radius. The part program was organized into four machining sequences that provided a 0.010 inch depth-of-cut for both the semi-finish and finish contour cuts.

The compensation demonstration used two dog bone inserts, one for each of the two contours. The first contour was semi-finsh cut with a new insert and then finished cut, using the same insert, with no tool path compensation. A second, new insert was installed in the lathe and the semi-finish cut of the second contour was completed. An OTICS inspection of the insert was then performed and the results used to compensate the tool path for the finish cut. The finish cut of the second contour was then completed. Figure 8 illustrates the test part configuration and the two cutter paths utilized in the test.

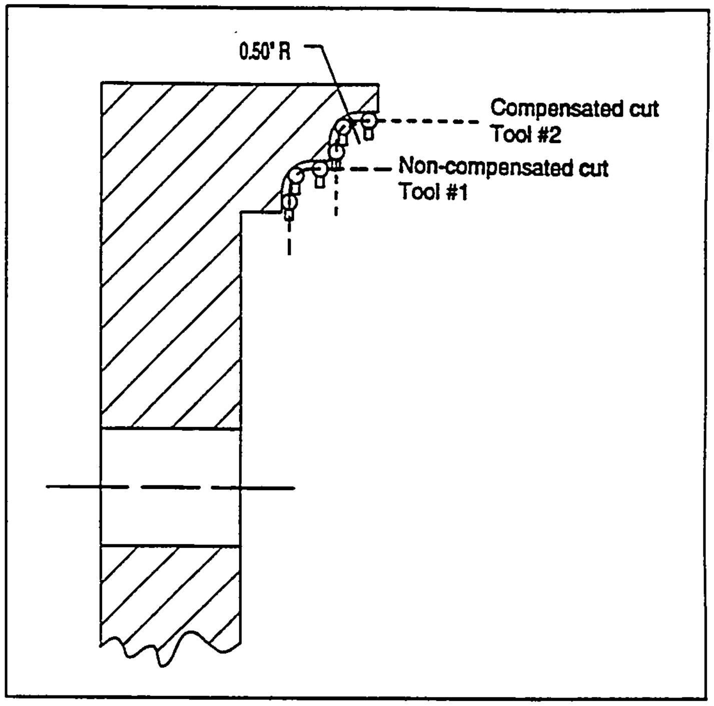

Figure 8. Tool paths used for compensation test.

Since the compensation software executes on the same IBM-PC used for the tool inspection, it was necessary to load a copy of the original part program into the PC and then transfer the compensated program back to the NC controller to complete the final finish cut. For purposes of the demonstration, the part program transfers were accomplished using a floppy diskette, mylar tape and "sneaker net". For a production implementation of the OTICS system, the local PC used to inspect the tools and compensate the program would be networked to the shop DNC system. Also, the inspection and compensation operations were manually initiated for the demonstration test, but provided the appropriate interface existed between a production lathe and the OTICS computer, all inspection and compensation operations could be automatically initiated by the NC part program. This approach has been demonstrated with the enhanced T-base lathe project at Y-12.

In addition to the single OTICS inspection of the second cutter used for the compensation process, tool shape inspections were performed for both cutters, before and after each cut. These inspections were collected to provide additional information on the shape change of the tools resulting from the machining operations. The results of the tool inspections are shown in figures 9 and 10. The plots of the tool shape are shown as deviations from a nominal 0.125 inch radius tool as inspected over a 90 degree segment of the cutter. The inspections plots indicate both inserts experienced similar wear and the maximum tool form error was approximately 0.0005 of an inch. It is important to recall the tool inspection used for compensation is referenced to the current 0 & 90 degree tangent points of the tool and not prior inspections. If these points wear more than other locations, the tool may appear to increase in radius. This type of inspection is valid for the compensation process which relies on controller axis offsets to account for wear at the tangent points.

After the finish cuts had been completed on the two test contours the part was taken to a DEA coordinate measuring machine (CMM) located on the shop floor. Both contours were dimensionally inspected to determine shape errors with respect to the nominal 0.5 inch radius contour. The CMM program was designed to locate the centers of the nominal radii from the straight sections machined with the test contours. Two inspection points were

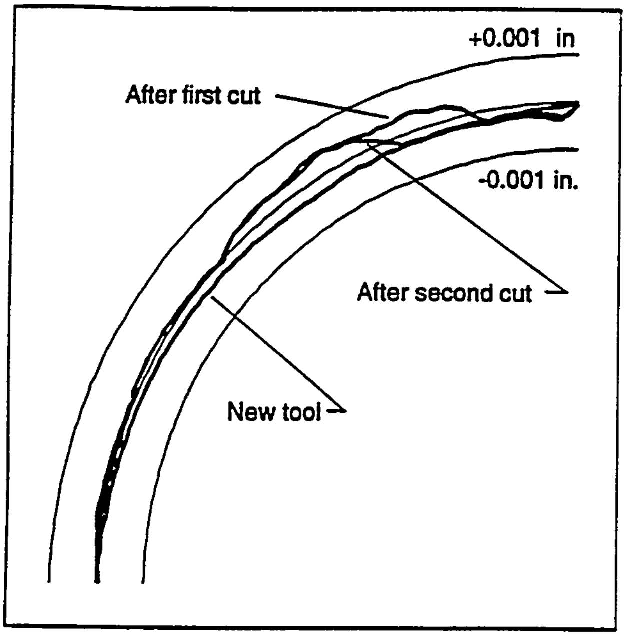

Figure 9. Tool profiles measured for non-compensated tool.

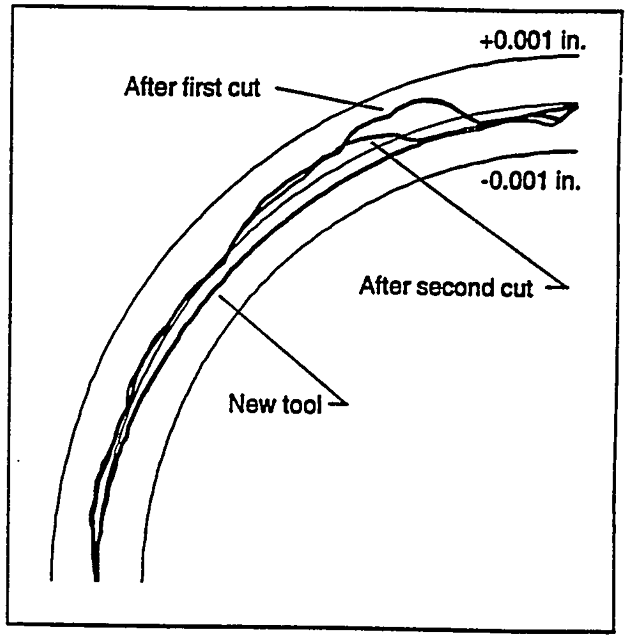

Figure 10. Tool profiles measured for compensated tool.

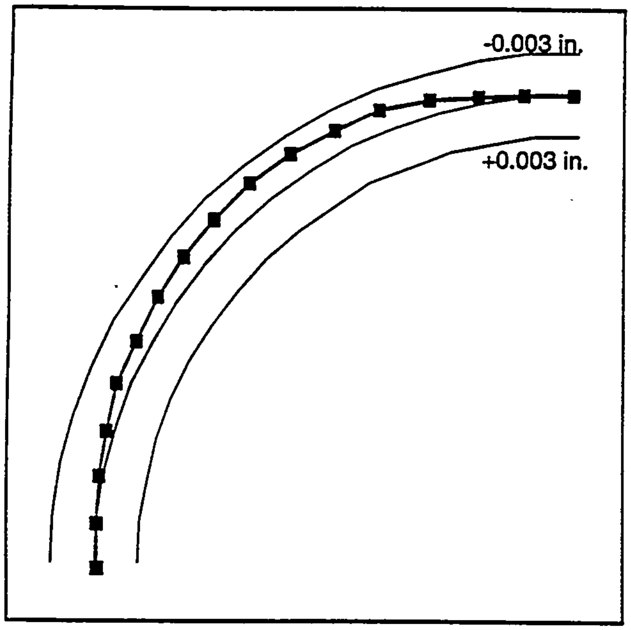

Figure 11. CMM inspection of non-compensated contour.

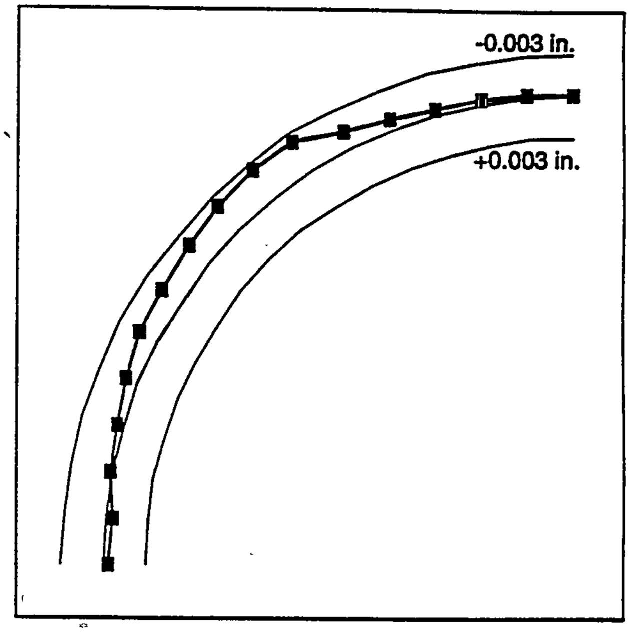

Figure 12. CMM inspection of compensated contour.

collected on each straight section and the inspection data was subsequently shifted to establish a minimum of error related to the straight sections. This process allows the location of the contour to "float" and simplifies the interpretation of the inspection results, since as discussed earlier, the compensation process affects only the shape of the contour not its location in the part.

Each contour was inspected at seventeen locations and plots of the inspection data for the two contours are shown in figures 11 and 12. The overall appearance of the contour errors are similar for both the compensated and non-compensated cuts. The compensated contour has a maximum error of 0.0024 inch and the non-compensated contour has a maximum error of 0.0019 inch. While the measurement precision of the CMM (0.0003 in.) is almost at the level of the difference of the maximum errors, it is interesting to note the contour error is approximately four times greater than the maximum tool error detected (0.002 in. vs. 0.0005 in.). While no benefit in the contour was measured for this single demonstration of the compensation process, it is apparent there are other factors in the machining process that are of greater magnitude than the tool shape errors. To further verify the compensation process, the relative block-by-block motions of the NC part program were plotted, shown in figure 13, for both the compensated and non-compensated cuts. The tool error inspection data used for the compensation process is also shown in figure 13 and the plots establish that the correct compensation was calculated.

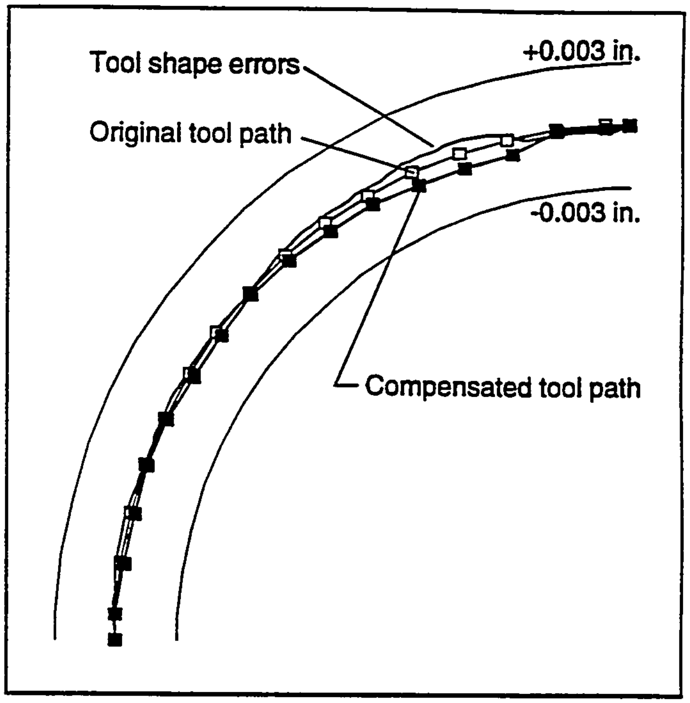

Figure 13. NC tool path for compensated contour overlayed with tool profile.

Excess material left on the part due to tool deflection is one possible process factor that would result in contour errors like those measured in the test. Assuming the tool and holder deflect away from the part as it is being cut, excess material would be left on the machined surfaces and the resulting actual contour radius would be smaller than the target of 0.5 in. An illustration of this excess material is shown in figure 14 and is depicted as being uniform in thickness along the radius and straight sections. One might speculate if excess material was left on the part, the inspection errors would have a positive sign instead of being negative values (lack of material) that were measured. However, if the inspection data for the condition of tool deflection is shifted to align the straight sections, the smaller radius would result in negative contour errors. This shifting of the inspection data is precisely what was performed with the actual inspection data. Figure 15 illustrates the contour errors resulting from inspecting a smaller radius aligned in this manner. The amount

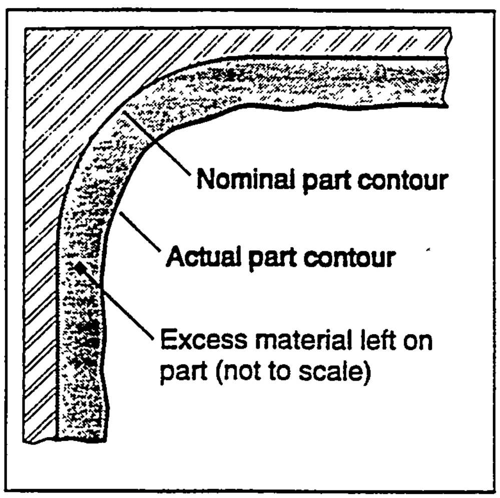

Figure 14. Illustration of material left on part due to tool deflection.

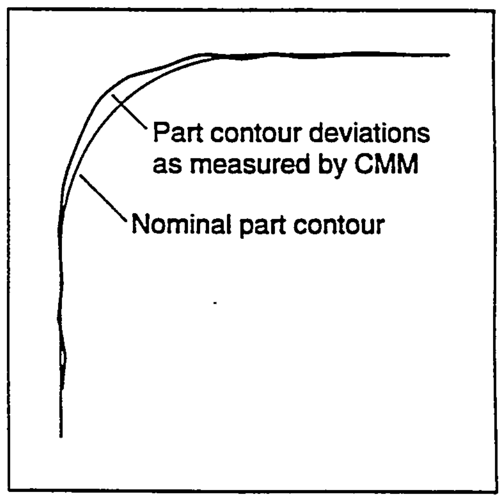

Figure 15. Illustration of CMM inspection of shifted contour.

of excess material depicted in figures 14 and 15 is exaggerated for illustration. In actuality, a radius that is 0.002 in. smaller would have a maximum contour error of approximately 0.001 in. located at 45 degrees. Other factors were no doubt present in the actual test, for example, equipment problems resulted in most of the compensated cut being machined with little or no coolant supplied to the part.

Summary

The tool wear measurement capability of OTICS was successfully evaluated in the Phase-1 testing. The testing verified that OTICS can easily detect tool wear and the +/- 0.0001 inch resolution obtained was sufficient for the larger cutter inserts used by P&W. It should be noted that some of the tool wear values obtained were for cuts with machining parameters (depth of cut, surface speed, and feed rate) well outside the normal process range in use at P&W. Indeed, one potential use of OTICS is a fast, objective gauge to quantify tool wear in machinability tests.

During the tool wear experiments at P&W, a second potential use identified for OTICS was the accurate on-machine dimensional verification of special ground contour forming tools. These tools are used with a plunge cutting motion to create the part contour from the profile of the cutter. Any errors in the profile of the cutter will be reflected in the part contour, thus it would be beneficial to assure the profile is within tolerance limits before each cut. While the OTICS software can not presently inspect a formed tool, the algorithms used to calculate tool wear could be extended to include the tolerance limits and profile analysis needed to inspect form tools.

The OTICS tool path compensation experiment demonstrated the varied technologies that are integrated in the tool path compensation process. The OTICS system was successful at inspecting the 0.125 in. radius tool and compensating the tool path for tool form errors. The need for automated interfaces between the OTICS computer and controller along with the part program requirements and the overall compensation methodology were highlighted in the demonstration. While the single contour cut used in the experiment was insufficient data to evaluate the benefit of tool path compensation, it did indicate that factors other than the tool geometry are a larger source of error for the machine used in the contour cutting test. Additional testing that quantified these other factors would be required to before a valid assessment of the compensation process could be completed. In general, unless the tool geometry errors are a significant source of the process error any benefit of tool path compensation is negligible.

DISTRIBUTION

Department of Energy, Office of Patent Counsel
R. M. Poteat, FOB/3067

United Technologies, Pratt & Whitney Division
400 Main Street, Mailstop 118-38
East Hartford, CT 06108
John Centola (5)
Wayne Zorger
Walter Serafin
Bob Lavery
Frank Pijar

Lockheed Martin Energy Systems, Inc.
E. F. Babelay, MS-8068, 9201-3
W. E. Barkman, MS-8068, 9201-3
B. B. Bovee, MS-8242, 701SCA
E. L. Epple, MS-8084, 9203
H. L. Gerth, MS-8068, 9201-3
J. E. Keyes (2)
A. K. Lee/DOE-OSTI (2), MS-8175, 9983-30
D. R. Patek, MS-6011, 3546
D. W. Post, MS-8097, 9202
K. W. Tobin, MS-6011, 3546
Y-12 Central Files, MS-8169, 9711-5