Compensation Of Residual Form Errors In Precision Machined Components

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Abstract

This paper describes a compensation technique for the correction of repeatable rotationally-symmetric residual form errors in precision machined components. Details of the FTS2TPG[†] software package, that connect a family of manufacturing equipment and metrology instrumentation together in a compensation cycle, are reviewed. In addition, examples are shown that demonstrate the level of compensation achievable with this technique.

Introduction

Two of the manufacturing processes capable of producing accurate aspheric optical surfaces are single point diamond turning (SPDT) and bound abrasive grinding performed on a diamond turning lathe. These processes produce surfaces with sufficiently small residual form errors to satisfy the tolerances of many demanding optical application. As with all manufacturing processes, the form errors produced by these processes have unique geometrical characteristics (signature errors). When these residual form errors are both rotationally symmetric and repeatable between machining sequences it is possible to reduce them by machining compensation.

The compensation technique described in this paper is represented by the cycle of events shown in Figure 1. The compensation cycle begins with the description of the desired aspheric surface. The description is entered, along with relevant tool geometry and machine information, into a software program that creates appropriate tool path motions for the surface's generation. This software program is the Tool Path Generator (TPG) system. These motions are then downloaded to an ultra precision turning lathe (*e.g.* an ASG-2500) which produces the precision component. The component is then removed from the lathe and measured for form accuracy on a Form Talysurf. The data from the Form Talysurf (FTS) is analyzed in the FTS's aspheric analysis program which yields a diametrical trace of the residual form errors of the surface as contrasted with the theoretical desired asphere. The cycle is then closed by software that uses the data of the diametrical surface trace to adjust the edge-to center machine tool path and permit the re-machining of the component to remove these errors. This software program is appropriately entitled FTS2TPG (Form Talysurf to Tool Path Generator) because it links these two key elements in the cycle.

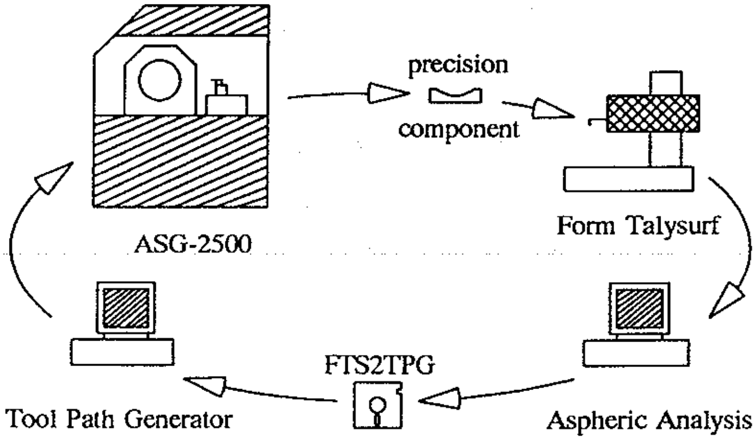

Figure 1 - Compensation Cycle

[†] Form Talysurf is a registered trademark of Rank Taylor Hobson Ltd.
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FTS2TPG Software Considerations

The FTS2TPG software uses data from a diametrical surface trace to adjust the edge-to-center machine tool path and thereby compensate for residual form errors. It accomplishes this by generating from Form Talysurf output an error template that can be overlaid on the tool path. The template approach is very versatile and has demonstrated it ability to compensate for the residual signature errors of single-point diamond turning and precision grinding. The process of overlaying the template requires the tool path generating program to identify the machining point with the tool path geometry. Understanding how the error template is generated is the most important of these considerations.

When the error trace from the Form Talysurf is loaded into the FTS2TPG program several events occur. The data points of the error trace are initialized, re-oriented, folded and spatially filtered prior to the generation of the template. The initialization and re-orientation of the data addresses the trace's radial asymmetry with regard to the calculated aspheric center. The data is re-oriented so that the shorter branch of data has positive radial values. The data is then folded so that each point on the positive branch is averaged with an interpolated value from the negative branch to account for mismatches in individual point positions. Only data that exist on both sides of the calculated center is folded. The folded data is then filtered using a "running average" algorithm. This filtering removes the effects of surface texture from the form data. The filtering results in a loss of approximately three percent of data from the edge of the folded trace.

The template is generated from this data by linear interpolation. The template consist of 500 points uniformly spaced in the radial direction. The template is adjusted in height so that the center point is at the origin. The choice of 500 points was made because this number is both consistent with the typical number of folded trace points and the typical number of tool path points. Also, the use of 500 points permits the user to review all template values graphically on a computer screen with 640 by 480 pixel resolution. The template approach has proven successful in compensating for many common residual form errors, including: errors resulting from tool waviness, sizing, and offsets; lead-on and central depressions typical in bound abrasive grinding; distortions due to local coolant effects; "step-like" discontinuities arising from material variations; and deformations due to dynamic machining effects. Many of these signature errors are poorly fit by low-order curve fitting routines but well fit by the template approach.

The process of overlaying the template on the tool path requires a correspondence between surface points and points on the tool path used to generate the surface. Figure 2 shows what is meant by the term tool path and how its locus differs from the surface geometry. This correspondence is provided by the Tool Path Generator when it creates the file of points that defines the tool path. Each CNC machining block of code consist of a line number, an x and z tool path position, and a commented surface coordinate that corresponds to this tool path position. An example of the block structure is shown below. FTS2TPG uses a scheme where the x coordinate of the surface is used to determine where the template should be overlaid and an interpolated z error is subtracted from the z coordinate of the tool path to effect compensation. Because tool paths usually start in space off of the surface to be machined extrapolation of the template must be considered. In FTS2TPG extrapolation is achieved by continuing the extreme point of the template to all machining points beyond the template region. This prevents discontinuities at the start of the template region.

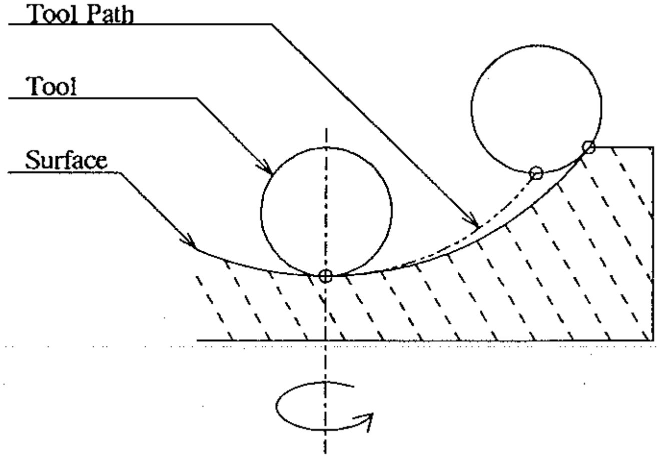

Figure 2 - Tool Path vs. Surface

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N0182 X+010.02824 Z-000.49786 (9.9294 -0.4930)
N0183 X+009.97799 Z-000.49288 (9.8787 -0.4880)
N0184 X+009.92774 Z-000.48301 (9.8300 -0.4831)
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An example of a typical sequence of CNC tool path blocks (note that the corresponding surface coordinates are placed in comments after the tool path position)

Compensations Examples

The effectiveness of this compensation technique can be demonstrated for both coarse (multiple micrometer) and fine (sub-micrometer) errors. The two examples reviewed in this section demonstrate both levels of error compensation. The first example consist of compensating for a predetermined aspheric zone, ten micrometers deep, intentionally machined into a surfaces. The second example demonstrates compensation for a typical tool centering (ogive) error on a fine single point diamond turned surface.

The first example demonstrates coarse compensation by the following scheme. A tool path was created for a surface with a ten micron deep zone created by the addition of two high-order polynomial terms. This surface was then diamond machined and measured as an aspheric referenced to the surface without the zone. This information was then passed through FTS2TPG and the original tool path was compensated. This compensated tool path was then compared with a tool path that did not have the additional zone and the results tabulated.

The surface used for this demonstration was machined in a 25 mm diameter brass sample. The surface consisted of a convex paraboloid of revolution with additional 8th and 10th order polynomial terms used to define the ten micrometer deep zone at 89 percent of the diameter. The sagitta equation for this surface is given below:

$$z=\frac{cx^2}{1+\sqrt{1-(k+1)c^2x^2}}+a_8x^8+a_{10}x^{10}$$

where: c is -0.01 mm; k is -1.0; a_8 is -1.8037×10^{-10} mm^{-7}; and a_{10} is 1.1183×10^{-12} mm^{-9}. Figure 3 shows the shape of the zone created by these two high-order polynomial coefficients alone. This is a particularly severe zone to measure since the asphericity due to the parabola alone is ten times less than the zonal error.

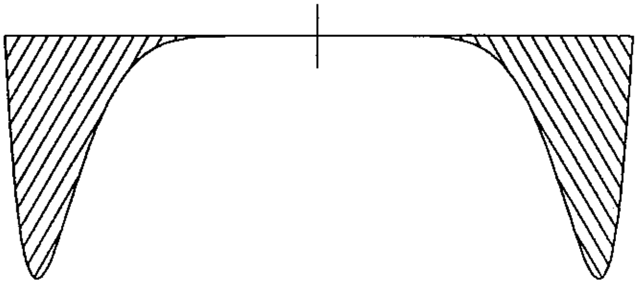

Figure 3 - Ten Micrometer Zone Error Profile

The comparisons between the tool paths before and after the application of the compensation with the pure paraboloid are shown in the table below. This data displays several features of the compensation technique. In the "before compensation" data the error is a result of the high-order polynomial aspheric term. The values start at zero and decreases to a depth of 10 micrometers between 11 and 12 millimeters and returns to zero at the physical edge of the part. Since tool paths begin off the surface the value at 13 millimeters starts to show the dominant effect of the tenth order polynomial term. In the "after compensation" data the error over the physical surface has been compensated to less than one-third micrometer. The data filtering effects are easily seen off of the surface. There the filtering algorithm causes the compensation to end before the physical edge of the surface and coupled with the extrapolation results in inconsequential errors off of the surface.

radial position (mm)	error (μm) before FTS2TPG	error (μm) after FTS2TPG	radial position (mm)	error (μm) before FTS2TPG	error (μm) after FTS2TPG
0	0.00	0.00	7	-0.75	0.14
1	0.00	0.01	8	-1.87	0.22
2	0.00	-0.01	9	-3.94	0.29
3	0.00	-0.02	10	-6.93	0.27
4	-0.01	-0.01	11	-9.68	0.06
5	-0.06	0.03	12	-8.26	0.02
6	-0.25	0.07	13	7.13	15.37

The next example of compensation, which is at the sub-micrometer level, is typical of the intended application for FTS2TPG. An aspheric surface consisting of a conic term and a series of higher-order polynomial terms was diamond machined in an aluminum alloy. After the initial diamond machining, the 17 mm diameter surface was measured on the Form Talysurf and exhibited the form error shown in the upper portion of Figure 4. This form error is typically caused by tool offset (ogive) effects. After application of FTS2TPG and re-machining the surface was re-measured and analyzed to have the form error shown in the lower portion of the figure (note that the vertical scale in the two figures are different). This reduction in form error from greater than one-quarter wave ($\lambda = 632.8$ nm) to better than one-tenth wave was accomplished by one additional machining pass. This example represents about the limit of compensation available with this technique.

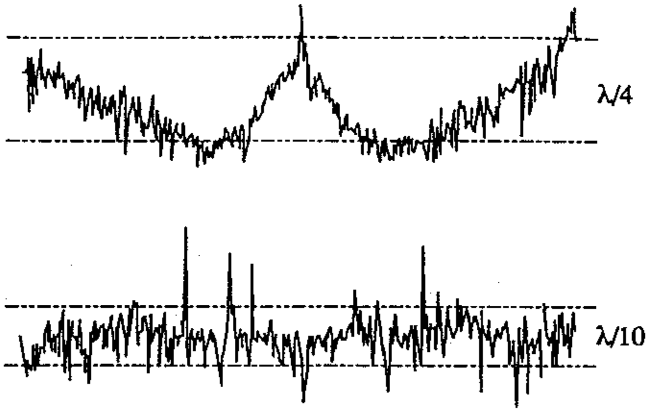

Figure 4 - FTS2TPG Compensation

Conclusion

This paper has demonstrated a technique for the compensation of residual form errors in precision machined components. By describing how the FTS2TPG software package connects measurement results with manufacturing information a compensation cycle can be constructed. Examples were given that demonstrated the working of the system and the level of compensation achievable.

Submitted for presentation at the SIRA Conference on Commercial Applications Of Precision Manufacturing
At The Sub-Micron Level, London, United Kingdom, November 21, 1991, SPIE Proceedings Vol. 1573.