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Engineering and
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MASTER

CORRECTING FORM ERRORS IN NUMERICALLY
CONTROLLED MACHINED, POINT-DEFINED,
SURFACES OF REVOLUTION

F. H. Broome
P. J. Anderson

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the ATOMIC ENERGY COMMISSION under U. S. GOVERNMENT Contract W-7405 eng 26

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ABSTRACT

Repeatable errors in parts manufactured by numerically controlled, single-point machining processes can now be corrected.

By applying empirical corrections, developed from inspection data, to the contour description, form errors in the inner contour of an approximately four-inch-radius hemispherical copper assembly were reduced from 600 microinches total variation (± 300 microinches from the desired dimension) to 200 microinches total variation (+ 120 microinches, - 80 microinches from the desired dimension).

The method can be readily applied to the APT programming system and is relatively inexpensive since, by using it, it is not necessary to rewrite the entire APT program.

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SUMMARY

Occasionally, it is necessary to fixture piece parts for single-point machining operations in such a manner that the machined surface cannot be fully supported from the back side. In a recent case, the back surface of a part was very irregular because some cooling tubes had been soldered to the surface. The part was fixtured with vacuum on a machined flange located near the waist. In another instance, the surface to be machined was in an assembly and so located that the back surface was inaccessible for fixturing. Vacuum and tool forces, generated while machining these unsupported surfaces, resulted in form errors approaching 1000 microinches even though the machine tool had a demonstrated tool-path accuracy of one-tenth this amount. In each case, empirically compensated machining tapes were prepared from inspection data and were successfully employed to reduce these form errors to 200 microinches. This method is inexpensive, predictable, and readily handled by APT programming; it requires only that the errors be of a repeatable nature. Only errors introduced by fixturing are discussed in this report, but the process is suitable for correcting form errors introduced by other sources, including the machine tool itself.

INTRODUCTION

Generally, the inherent accuracy and precision of numerically controlled machine tools are sufficient to produce piece parts of the desired quality without resorting to such techniques as modified control tapes. Occasionally, however, the quality of the machine tool cannot be fully realized in the machined part. For example, tool wear from machining a very large surface of an abrasive material such as stainless steel or nickel may result in form errors in excess of the piece-part tolerance, although the tool path may be well within the required limits; or piece-part geometry may be such that well-designed tooling cannot support the piece part sufficiently to prevent distortion of the part under the forces created by the machining process or the fixture itself.

If the errors from whatever source can be proved to be repeatable, the method described in this report can frequently be employed to reduce these errors to an acceptable level.

DISCUSSION

MACHINING PROCESS

Considerable time and money have been spent throughout industry to make the process of producing surfaces of revolution with numerically controlled, single-point machine tools relatively straightforward and free from variables. But even with the best available machine tools, carefully designed tooling, and highly skilled operators, there are times when this process is not enough and some supplementary method must be employed to produce in-tolerance piece parts. With duplicating lathes, the method of modifying the tool-to-stylus ratio has been developed and is now an acceptable technique. Although more sophisticated, the method of preparing compensated machining tapes for numerically controlled machine tools is a logical extension of this technique.

One of the part types encountered while developing this method is shown in Figure 1. The assembly consisted of two concentric copper hemishells brazed to a copper base ring. A tube was brazed to the outer shell at the pole. Concentricity, squareness, and radius tolerances dictated that the inner spherical

Figure 1. VACUUM MACHINING FIXTURE AND UNSUPPORTED PIECE PART.

radius be machined after the assembly was furnace brazed together, a process which left the copper in a dead-soft condition. A total radius and roundness tolerance of 100 microinches (minus) was allowed on the approximately four-inch inner-spherical radius.

Obviously it was not possible to fixture on the inner shell, since it was not exposed. The only reasonable way to hold the part appeared to be fixturing in a full-fitting vacuum pot chuck on the outer surface of the outer shell, as shown in Figure 1. However, this method left the inner shell unsupported except at the waist, and it also subjected the inner shell to unpredictable vacuum forces through the hole in the tube. Previous experience with machining parts that were not fully supported suggested that problems might be encountered, so the first control tape was prepared to machine the part leaving six mils of stock on the part radius. The machine used was a numerically controlled turning and boring machine equipped with an air-bearing spindle and automatic tool setting. A 27-mil-radius diamond tool was employed with a commercial oil for the coolant. The oil was supplied from squeeze bottles that had been filled the previous day to allow the oil to reach thermal equilibrium near the machine before use. This procedure eliminated the need for a heat exchanger to maintain the coolant temperature in the machine's coolant tank. After machining, the part was removed from the machine and inspected on a sweep gage which was mastered to the radius programmed in the tape. The results of this inspection are given in Figure 2. As can be seen, the contour varied a total of 600 microinches, with a maximum one-direction error of + 300 microinches occurring about 30 degrees from the waist. Using these data, a second control tape was prepared. The contour was corrected every ten degrees, and a linear variation between latitudes was assumed. A nominal radius was programmed that was three mils larger than the original radius, leaving three mils of stock on the part. One pass of two mils and one pass of one mil were used. Again, the part was machined and inspected with the results indicated in Figure 3. Much of the form error had been eliminated, but the polar and waist regions still had considerable room for improvement. These data were used to prepare a final control tape which was used to machine the part to the desired radius in two passes. The first removed two mils and the final pass, one mil. Again, corrections were applied every ten degrees and a linear variation between latitudes was assumed. After final machining, the part was inspected. The results of this final inspection are shown by the trace in Figure 4. A total variation of 200 microinches remained in the part with a maximum one-direction error of + 120 microinches occurring about 20 degrees from the waist.

It is not likely that further improvement could have been effected, since errors of this magnitude could not reasonably be assumed to be repeatable and since a portion of the error must be assumed to be gage error.

Figure 2. ERROR CURVE AT -0.006 INCH FROM DESIRED RADIUS.

Figure 3. ERROR CURVE AT -0.003 INCH FROM DESIRED RADIUS.

Figure 4. FINAL ERROR CURVE AT THE DESIRED RADIUS.

COMPENSATING THE CONTROL TAPE

The original or uncompensated control tape is prepared by taking the desired geometric shape (ie, line, circle, ellipse, parabola, cone, or point-defined contour) and programming the tool path by offsetting a cutter radius plus a predetermined amount of stock. The tape is then used to machine a part leaving the predetermined amount of stock. Even though this operation could be considered semifinishing, the same care required in finishing must be exercised to obtain reliable compensation data.

After initial machining, a complete inspection must be made. A continuous-path form of inspection is desired so that the location and magnitude of all errors may be determined. However, without continuous-path numerically controlled inspection equipment, this type of inspection is impractical for shapes other than lines or circles. For other shapes, a point-to-point inspection will suffice provided the point density is sufficient to approximate the location and magnitude of all errors within the range of compensation. For most point-defined contours, the number of inspection points should be the same as the number required to define the part.

Using these inspection data, a compensated tape is then made by redefining the desired shape (ie, line, circle, or ellipse) into a new shape using the cubic-spline curve-fitting routine, which is known as Tabcyl in the APT system.^(a) The input should be evenly spaced points different from the points on the original shape by the amount of the determined error. The surface between points is then "faired" analytically in the same manner as all other point-defined contours. The compensated tool path is offset from this new shape by an amount equal to the cutter radius.

From a tape preparation standpoint, the accuracy of the method is limited only by the repeatability of the errors, measurement reliability, and resolution of the machine control unit.

(a) Fowler, A. H. and Wilson, C. W.; Cubic Spline, a Curve Fitting Routine, Y-1400 Rev 1; Union Carbide Corporation-Nuclear Division, Y-12 Plant, Oak Ridge, Tennessee; June 28, 1966.

CONCLUSIONS

The method of correcting form errors through compensated contours should be recognized as a final supplement to, rather than a replacement for, well-maintained machine tools and well-designed fixtures and procedures. When tool wear or insurmountable fixturing problems create a condition which produces out-of-tolerance form errors on a numerically controlled machine tool with adequate tool-path accuracy, compensating the machining tape for repeatable errors provides an inexpensive method which will frequently reduce the form errors to an acceptable level.