MASTER

ACCURATE MACHINING

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Introduction

Most machining processes do not require exceptional accuracy. Therefore, few conventional production machines are designed to produce parts with contour accuracies greater than 0.0001 inches or surface finishes better than 4μ inch RMS. For those very few instances in which great accuracy is required, a whole series of new considerations must be evaluated and their resulting problems solved. For example, any change in length of the machines' spindle (called spindle growth) results in unacceptable machine accuracy. Most researchers use air bearing spindles which have very low internal friction and some cooling through the air supply temperature and these in turn reduce the spindle growth. (1,2) Cutting processes are inherently heat generating processes so that further cooling of the entire machine is needed to prevent errors caused by varying rates of thermal expansion of the workpiece and the numerous machine components. Again, the most common solution is to produce a special room with precise temperature control. Vibration transmitted through floors and machine supports as well as unbalanced rotating machine components can also produce errors. Some "upgraded" conventional machines have been virtually rebuilt using special electrical motors and very thin "sanded down" drive belts to eliminate on-the-machine vibration sources. (3) Furthermore, most of the machines are mounted on air suspension legs which are very soft air springs with automatic leveling controls to isolate the machine from vibration transmitted through the foundation.

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Additional manufacturing errors are attributable to the cutting process itself. Conventional tungsten carbide inserts are very acceptable for the usual accuracy requirements. A much more accurate tool is required when going beyond the usual industrial configuration and surface finish accuracies and therefore very hard materials such as diamond are used for cutting tools.⁽⁴⁾

Although there are many additional problem areas such as finite randomly oriented grains, and variations in grain-grain boundary properties of the workpiece which are common to all high accuracy machining, two major areas of machine tool design problems exist. These problem areas involve the straightness of the slides used to produce a contour and the inaccuracy of lead screws and related actuator systems. Many current high accuracy machines use either an X-Y linear slide produced motion or a rotory-slide system called the r- θ machine. However, at Rocky Flats, the approach used is based on all rotory motion with no slides, produced with special electric drive motors. Details of the latter system will be given below.

High Accuracy, All Rotory Machine

One approach to the elimination of slide and actuator errors is to produce a machine with no slides and a perfectly smooth actuator drive force. Even the best slides still possess minute inaccuracies. Some investigators believe that the practical limit to slide straightness is about 4μ inches per foot of length and beyond that limit they are working on electro-optical compensation methods.⁽⁵⁾ Work is also being done on linear induction motor methods of eliminating lead screw errors.⁽⁶⁾ The ultimate in the compensation approach is an adaptive control system which

currently being studied.⁽⁷⁾ Two weaknesses of the compensation approach are: (A) Each machine must be "custom made", installed and not be moved from its location or uncompensated error may creep in; (B) Adaptive control handles repetitive errors well but cannot adapt for random or non-repetitive errors, for the machine must learn from its previous mistakes to some extent and a "non-experienced" or non-anticipated source of error or one that does not occur in a predictable fashion cannot be guaranteed to be subject to the machine's compensation system. Even an interferometric compensation system, depends upon some error or path deviation having already occurred before compensation comes into play. So compensation can reduce a tendency to continued deviation but cannot eliminate all errors or produce a perfect contour path since an initial error must occur first.

The Rocky Flats approach involves the use of three axes to produce the motion needed for aspheric part contours. For purpose of cleanliness of the machine, two axes are vertical and are located on the top of the machine as in Figure 1. On one axis, a tool arm is mounted perpendicular to the vertical axis and being of constant length (no slides) describes a circular path when rotation occurs about its vertical axis. On the second, parallel vertical axis, a part turning spindle is mounted with its axis perpendicular to the vertical axis so that rotation of the vertical axis then moves the part holding spindle's axis in a horizontal plane like that of the tool arm as in Figure 2. On the actual machine, each axis described is in fact an air bearing system. The air bearings which are commercially produced items are very resistant to a shift in axis position through applied forces but are almost frictionless in the rotation

about the axis. Therefore, motion about the axis is very smooth and very accurate. The machine axis system is summarized in Figure 3.

Any desired contour may be produced as illustrated in Figures 4 and 5 which show three positions on a parabolic part contour and a flat part respectively. The two vertical axis air bearings must rotate at different rates and in some cases, the motion of one of them must reverse direction to produce a contour. All of the variables in the motion needed to produce various contours have been analyzed and numerous examples have been calculated on a digital computer. Comparative contour accuracies between the all rotory machine and slide machines have also been studied for real machine components.

Since the two vertical spindles rotate at different rates to achieve the needed location of the tool point on the part contour, angular digital encoder equipment is placed on each axis to identify the angular position at any time. The very accurate angular encoders were designed and produced by Optics Technology Inc. and their most advanced system was obtained for use on the all rotory motion machine. Baldwin also produces a comparable angular encoder system which is within a factor of two of the accuracy of the system being used.

Finally, a commercially available tape control system is used to select and control vertical axis rotations needed to produce the contour desired. The whole system is mounted in an environmentally controlled room. The machine is mounted on air suspension legs and diamond tools are used just as with other high accuracy systems. The actual machine incorporating the all rotory motion feature is shown in Figure 6.

A constrained all rotory machine dubbed the phonograph configuration

is being used to produce flat parts as shown in Figure 7. Such a concept has been used by other investigators.⁽⁸⁾ In the case of the phonograph configuration, only the two vertical axes are used. The part is mounted on one vertical axis and turned at constant angular velocity for machining. A tool arm is mounted on the second, parallel vertical axis as before. The flat geometry is then produced in a manner similar to a phonograph needle in playing a record, the diamond tool replacing the stylus and the part to be machined replacing the record.

The primary advantages of the all rotory systems are: improved accuracy, greater machine simplicity, and a reduction of chip material buildup through the inherent cleanliness of the design. The principal disadvantage is a greater complexity of the tape program needed to specify the appropriate positioning of the axes during machining. While tapes used on controllers have a "block length" or intervals over which the positioning occurs at constant velocity, the block length error on an X-Y machine is a series of straight line approximations to the contour, while that for the all rotory machine is a series of curves which much more closely approximate the desired contour. Block length error can be reduced on both types of machine by reducing the block length size but that correspondingly increases the total control tape length and soon goes beyond the capacity of most tape drive systems. Later plans are to incorporate a direct computer control which has been done on some conventional production machines. With a computer controlled system, the block length is reduced to the computing time needed to update the positioning data.

Determination of Accuracy Achieved

Presently, parts made on the all rotory system are inspected by

microscopy and interferometry methods using commercially available equipment. A new surface characterization approach is also being used which experimentally determines the Fourier components of the actual surface roughness using the diffraction of laser light. The technique and the associated equipment have been extensively reported in the literature as for example in reference 9.

Conclusions

~~of the all-rotary machine~~ of the all-rotary machine ~~very minor test part experience~~ has been obtained. Results at this point appear to verify that the machines (both in the three axis and in the phonograph configuration) are inherently more accurate than machines with slides. Much more work is needed to define the desirable operating parameters and the size capacity of the all rotary machine. A second generation three axis machine is in the design stage which abandons mounting the vertical axes from the top, and instead has three vertical axes at various pin points of link points on a complex tool arm. The part then spins on a fixed axis. This machine is conceived to produce large diameter contoured ~~parts~~ ^{large mirrors} with great accuracy. Going to a complex set of tool arm linkages greatly reduces the weight and forces on components to be moved during machining, reducing further the very minute deflection in the machining process.

REFERENCES AND NOTES

1. Donaldson, R. R., "A Simple Method for Separating Spindle Error from Test Ball Roundness Error," Ann CIRP, V. 21-1, pp 125-126, (1972)
2. Bryan, J. B. Donaldson, R.R., McClure, E. R., and Clouser, R. R. "A Practical Solution to the Thermal Stability Problem in Machine Tools," SME Tech. Paper #MR-72-138 (1972)
3. Gerth, H. L., Union Carbide Y-12 Plant - ~~Private Communication~~ *Private Communication*
4. Donaldson, R. R., "The Deterministic Approach to Machining Accuracy," 1st Annual Fab. Tech. Symposium Proceedings, Boulder, Colorado (October 1972)
5. Bryan, J. B., "The Role of Philosophy in Machine Tool Accuracy," 4th Annual Fab. Tech. Symposium Proceedings, Boulder, Colorado, November, 1975.
6. Thompson, C. H., Personal Communication.
7. Richards, J. B., ~~"Application of Automatic Tool Setting, Air Bearing Spindles, and Laser Interferometer Feedback to Machine Tooling," Report Y-12-1234, Oak Ridge Y-12 Plant (September 1966).~~ *Private Communication*
8. Arnold, J. B., Burleson, R. R., Pollock, C. B., Sveda, R. W., Sladky, R. E., Steger, P.J., and Woodall, N. D. ~~"Machining Accuracy," Report Y-12-1234, Oak Ridge Y-12 Plant (February 1976).~~ *Private Communication*
9. Stover, John C., "Roughness Characteristics of Smooth Machined Surfaces by Light Scattering," Applied Optics (August 1975).