Available online at www.sciencedirect.com
ScienceDirect
Precision Engineering 31 (2007) 169–176
PRECISION ENGINEERING
www.elsevier.com/locate/precision

Technical note

A flexure-based tool holder for sub-μm positioning of a single point cutting tool on a four-axis lathe

Matthew Bono *, Robin Hibbard

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, United States

Received 20 January 2006; accepted 27 March 2006
Available online 26 September 2006

Abstract

A tool holder was designed to facilitate the machining of precision meso-scale components with complex three-dimensional shapes with sub-μm accuracy on a four-axis lathe. A four-axis lathe incorporates a rotary table that allows the cutting tool to swivel with respect to the workpiece to enable the machining of complex workpiece forms, and accurately machining complex meso-scale parts often requires that the cutting tool be aligned precisely along the axis of rotation of the rotary table. The tool holder designed in this study has greatly simplified the process of setting the tool in the correct location with sub-μm precision. The tool holder adjusts the tool position using flexures that were designed using finite element analyses. Two flexures adjust the lateral position of the tool to align the center of the nose of the tool with the axis of rotation of the *B*-axis, and another flexure adjusts the height of the tool. The flexures are driven by manual micrometer adjusters, each of which provides a minimum increment of motion of 20 nm. This tool holder has simplified the process of setting a tool with sub-μm accuracy, and it has significantly reduced the time required to set a tool.

Keywords: Diamond turning; Tool setting; Tool holder; Single point diamond tool; Precision machining; Meso-scale machining; Lathe

1. Overview

Cutting parts on a lathe is one of the oldest and most versatile machining methods. Modern versions of the lathe include four-axis diamond turning machines, which incorporate a rotary table (*B*-axis) that allows the cutting tool to swivel with respect to the workpiece to enable the precise machining of complex workpiece forms. Many of these machine tools provide motion accuracy on the order of tens of nanometers, but in order to machine parts accurately on these lathes, the cutting tool must be positioned precisely at the correct height and in the correct lateral position on the rotary table. Setting the tool correctly requires special hardware that allows adjustments of the tool position with the required level of precision over an adequate range of motion in three degrees of freedom. This document describes the design and operation of a tool holder for precisely positioning a single point diamond tool on the *B*-axis of a four-axis diamond turning machine. The device is designed to be used on a commercial diamond turning machine and can adjust the cutting tool position in three orthogonal directions with 20 nm resolution. The tool holder uses flexure mechanisms to move the cutting tool, so there are no mechanical components that slide relative to each other, and therefore there are no potential detrimental effects from trapped friction. It also has parasitic error motion of less than 0.1 μm, so it enables tools to be set relatively rapidly to machine complex components with sub-μm accuracy. A photograph of the tool holder appears in Fig. 1.

2. Background

The four axes of a precision lathe are illustrated in Fig. 2. The spindle of the lathe is mounted on the x-axis, which moves the spindle and the workpiece toward or away from the operator. The z-axis supports the B-axis and the cutting tool, and it moves the cutting tool toward or away from the workpiece in the direction parallel to the spindle axis. The spindle itself is referred to as the C-axis and can be operated in either a free-spinning mode or in an angular positioning mode. The B-axis is a rotary table mounted on top of the z-axis and rotates the tool in the xz-plane so that it can swivel with respect to the workpiece.

* Corresponding author. Tel.: +1 925 422 5883.
E-mail address: bono1@llnl.gov (M. Bono).

0141-6359/$ – see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.precisioneng.2006.03.007

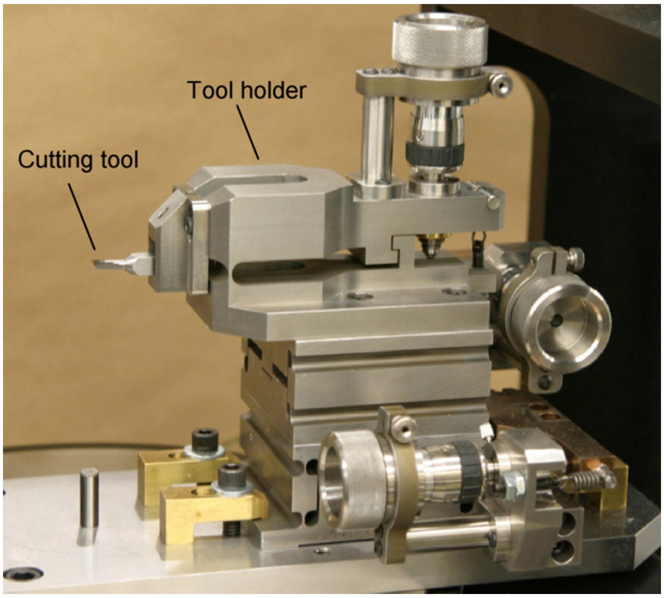

Fig. 1. Flexure-based tool holder.

The *B*-axis of the machine tool is used when machining parts with a complex shape, such as aspheres or oddly shaped lenses, and it is a crucial element to machining parts with both interior and exterior features, such as components for a double shell target [1]. Machining components with sub-μm accuracy on a four-axis lathe is not a trivial task, and there are several approaches that could be used to achieve the required accuracy. This study is concerned with the case in which the nose of the tool has a circular cutting edge with a conical clearance. The approach used in the current study is to position the center of the nose of the single point diamond tool along the axis of rotation of the *B*-axis. Aligning the tool properly requires a special tool holder that is mounted on the platform of the *B*-axis. To describe relative motion of the tool with respect to the *B*-axis platform, a coordinate system is defined that is fixed to the *B*-axis platform. The *i*, *j*, *k* coordinate system has its origin directly on the axis of rotation of the *B*-axis. The *i*- and *j*-axis are parallel to the *B*-axis platform, and the *k*-axis is parallel to the axis of rotation of the *B*-axis. The *k* direction is often referred to as the "height" direction. The tool holder maneuvers the tool in the *i* and *j* directions to center the tool nose with the axis of rotation

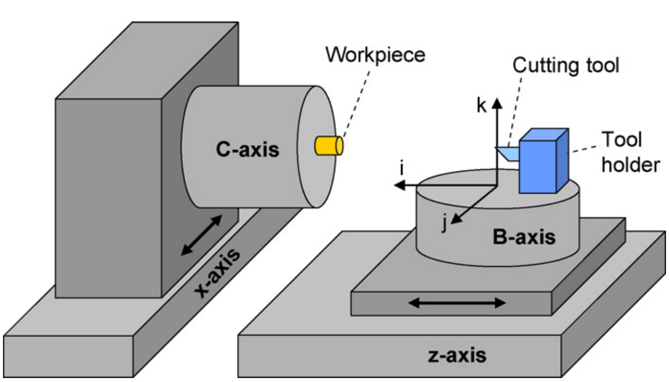

Fig. 2. Schematic illustration of a T-based four-axis diamond turning machine.

of the *B*-axis, and in the *k* direction to align the height of the cutting edge with the spindle axis.

In general, the accuracy of a machined workpiece surface is limited by the accuracy with which the tool is set, which often requires that the tool be positioned precisely on the *B*-axis. However, many commercial machine tools employ special procedures that can tolerate tool setting errors of several μm or more. Most industrial diamond turned parts machined on four-axis machine tools are either relatively large or have shallow profiles, such as lenses or molds. When machining parts such as these, an interferometer or displacement probe can be used to measure the profile of the machined part to map the error of the surface figure. The machine tool can then compensate for any workpiece profile error to machine the desired profile. This method corrects for any tool setting errors in the *i* and *j* directions, so there is no need to set the tool exactly on the axis of rotation of the *B*-axis. It is only necessary to set the tool at the correct height in the *k* direction. Commercial tool holders allow adjustments in the *i* and *j* directions using sliding plates that are preloaded with set screws and adjusted with differential screws. These mechanisms are not designed to allow sub-μm positioning of the tool in the *i* and *j* directions, but they provide a simple means of positioning the tool within a few μm of the axis of rotation of the *B*-axis.

Commercial tool holders exhibit some cross-talk, meaning that every time the tool is moved in one direction, it can move by more than 1 μm in the orthogonal directions, which complicates setting the tool with sub-μm accuracy in the *i*, *j*, and *k* directions simultaneously. In addition, each time the tool is adjusted, friction becomes trapped in the sliding components of the tool holder. If proper measures are not exercised, this trapped friction can be released in the form of incremental slipping of the sliding plates. This slipping can cause the tool to move several μm over the course of a few days, which further complicates the issue of keeping the tool centered precisely on the *B*-axis.

The commercial tool holders work well for their intended method of operation, when workpiece error compensation methods can be used. In contrast, error compensation methods are difficult to apply to meso-scale components with complex three-dimensional shapes, such as components for laser targets. These components often contain both interior and exterior features, or they are too complex or too fragile to be reliably measured. Therefore, the commercially available tool holders are not appropriate for certain complex meso-scale components with sub-μm profile requirements.

The profiles of meso-scale components with complex three-dimensional shapes must be machined correctly without performing direct, comprehensive metrology of the workpiece. Therefore, obtaining the correct workpiece form requires that the cutting edge of the tool traverse the correct path along the workpiece surface. One way to accomplish this task is to precisely position the nose of the tool on the axis of rotation of the *B*-axis. However, rather than placing the tool in a precise location on the *B*-axis, it would also be possible to establish a virtual axis in the *k* direction that passes through the actual location of the center of the tool nose. The machine tool could be programmed