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Tool setting on a *B*-axis rotary table of a precision lathe

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ABSTRACT

A method has been developed for setting a single-point cutting tool on the axis of rotation of a *B*-axis rotary table on a precision lathe. The method requires that three grooves be machined in the face of a workpiece with the *B*-axis set at three different angles. The depths of each of the grooves are then measured, and the measured values are used to calculate the tool offset vector. Experiments on a four-axis diamond turning machine have verified the precision of this method. This method has a significant advantage over commercially available touch probe tool set stations, because touch probes are well known to damage the cutting edges of fragile tools, such as single-point diamond tools with a small nose radius and a large primary clearance angle. The method developed in this study does not subject the cutting edge of the tool to any stress beyond that of its intended purpose of machining workpiece material. Therefore, this method can be used to set extremely fragile single-point cutting tools without the risk of damaging the tools.

1. Introduction

Single-point diamond turning is a versatile process for machining precise parts from a wide variety of workpiece materials. This study develops a practical method of aligning a single-point cutting tool along the axis of rotation of a *B*-axis rotary table of a precision four-axis lathe. This study focuses specifically on setting fragile single-point diamond cutting tools with a circular nose radius and a conical clearance. Tools such as this are used in the manufacture of meso-scale laser target components [1,2], for which workpiece geometries can require a nose radius as small as 5 μm and a primary clearance angle of up to 22°. The objective of the study is to identify a method that allows a fragile single-point cutting tool to be precisely set on the axis of rotation of a *B*-axis rotary table in a cost effective manner for use in a production environment on a precision lathe.

1.1. Layout of a precision lathe

The traditional design of a precision lathe includes a spindle that rotates the workpiece and two linear axes that move the cutting tool with respect to the workpiece. Some modern diamond turning machines also include a rotary table, or *B*-axis, that allows the cutting tool to swivel with respect to the workpiece to enable the precise machining of complex workpiece forms. To obtain accurate parts, the cutting tool must be positioned at the correct height and in the correct lateral position on the rotary table, which usually requires that the tool nose be centered on the axis of rotation of the *B*-axis.

The four axes of a precision lathe are illustrated in Fig. 1. The spindle of the lathe is mounted on the *x*-axis, which moves the spindle and the workpiece in the direction perpendicular to the spindle axis. 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 *B*-axis is a rotary table mounted on top of the *z*-axis and rotates the tool in the *xz*-plane. The fourth axis is the spindle, which usually operates in a free-spinning mode. However, it can also be used in an angular positioning mode and is referred to as the *C*-axis.

The *B*-axis rotary table 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. 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* axes are parallel to the *B*-axis platform, and the *k*-axis is parallel to the axis of rotation of the *B*-axis. A tool holder is used to adjust the tool in the *k* direction to align the height of the cutting edge with the spindle axis, and in the *i* and *j* directions to place the tool in the desired lateral position.

Programming a tool path to machine a workpiece is usually simplified if the circular nose of the cutting tool is centered on the axis of rotation of the *B*-axis, because motion of the *B*-axis will then cause the tool to simply rotate about the center of its nose without affecting the location of the cutting edge. In some cases,

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machine tools employ functions that compensate for tool-setting errors by periodically measuring the workpiece profile and adjusting subsequent tool passes. However, error compensation routines are difficult to apply to meso-scale components with complex three-dimensional shapes. These components often contain both interior and exterior features, or they are too complex or too fragile to be reliably measured. In these situations, the tool must be placed on the axis of rotation of the *B*-axis. The current study addresses this type of situation and develops a method for determining the offset from the center of the tool nose to the axis of rotation of the *B*-axis.

1.2. Classes of tool set stations

Several types of tool set stations are commercially available for four-axis lathes and two-axis lathes. Tool set stations for these two types of lathes operate on different principles. A two-axis lathe has only *x* and *z* linear actuators and a spindle, but no rotary table. The most common type of tool set station for a two-axis lathe uses a sensor that is mounted in a known position in the machine tool *xz* coordinate system [3,4]. By measuring the location of the tool cutting edge with the sensor, the position of the tool can be determined.

When setting a tool on a *B*-axis rotary table, the position of the sensor in the machine tool coordinate system does not need to be known accurately. The process of setting the tool places it in a known *xz* position along the axis of rotation of the *B*-axis. Therefore, there are no issues with the mechanical stiffness or thermal deformation of the structural loop between the sensor and the tool.

Several different methods are commonly used to determine the position of the cutting tool to facilitate setting it on the axis of rotation of the *B*-axis. Many methods measure the location of the cutting tool directly, using a contact probe or a vision system. Other methods indirectly determine tool position by measuring features on a workpiece that have been machined with the cutting tool [5]. The current study develops a method for determining the tool offset on a *B*-axis by measuring the depths of several grooves that are machined into a workpiece. This method has the advantage of being more precise than commercially available vision systems, and unlike commercial contact probe systems, it poses little risk of damaging fragile cutting tools.

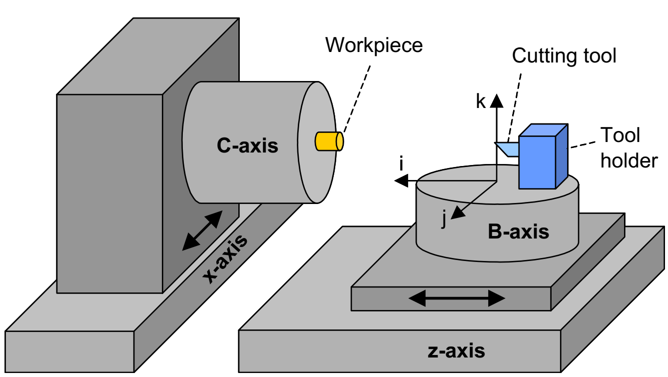

Fig. 1. Schematic illustration of a T-based four-axis diamond turning machine.

2. Machined grooves tool-setting method

The tool offset on a *B*-axis rotary table can be determined by machining three grooves into the face of a workpiece and then measuring the depth of each of the grooves. The workpiece used for this process is first faced to create a flat surface, and then several grooves are cut in its face using different *B*-axis angles, as shown in Fig. 2. To machine the first groove, the tool is plunged into the workpiece in the *z* direction and then translated in the *x* direction to machine a shallow groove. The tool is then retracted in the *z* direction off of the workpiece and moved in the *x* direction to a fresh spot on the workpiece. The *B*-axis is then rotated to another angle, and the tool then plunges back into the workpiece to the previous *z*-coordinate and translates in the *x* direction to machine another groove. This process is repeated once more, so that the workpiece contains three grooves, each of which was machined using a different *B*-axis angle.

The depth of each of the machined grooves is then measured. If the tool has a perfectly circular nose and is located on the center of the *B*-axis, then each of the three grooves should have exactly the same depth. However, if the tool is not located on the axis of rotation of the *B*-axis, then the relative depths of the three grooves can be used to calculate the tool offset.

Consider the situation depicted in Fig. 3, in which the initial groove has been machined into the workpiece with the *B*-axis oriented such that the *i* direction is parallel to the *z*-axis. The center of the tool nose is offset from the center of rotation of the *B*-axis by a distance *e*, which has components, e_i and e_j, in the *i* and *j* directions. θ is the initial angle from a vector in the *i* direction to a vector extending from the axis of rotation of the *B*-axis to the center of the tool nose.

If the tool nose radius is designated by *r*, then the distance from the machined workpiece surface to the center of rotation of the *B*-axis, h_o, is given by Eq. (1):

$$h_o = e\cos(\theta) + r \tag{1}$$

The *B*-axis is then rotated to an angle, α, to machine the second groove, as shown in Fig. 4. In the case illustrated, α is a

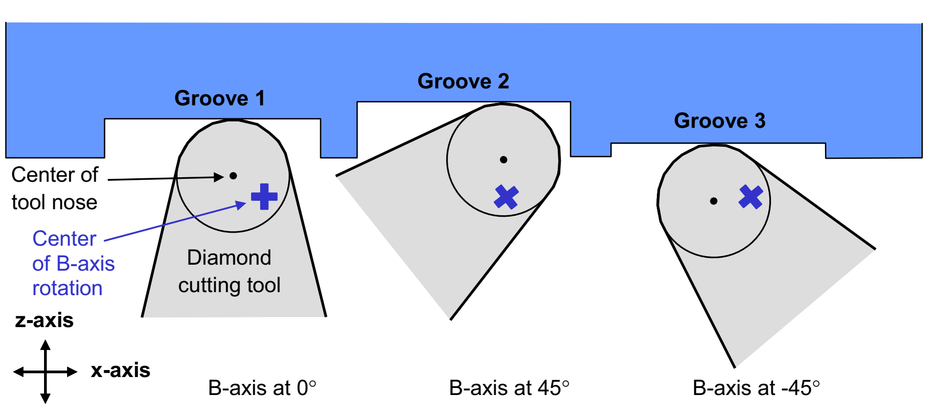

Fig. 2. Three grooves machined in the workpiece using different *B*-axis angles.