NOVEL ULTRAPRECISE TOOL ALIGNMENT SETUP FOR CONTOUR BORING AND BALL-END MILLING

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Abstract
Diamond turning and fly-cutting extend the spectrum of machinable surfaces and are commonly employed for ultraprecision manufacturing of complex surfaces and microstructures [1,2].
In contour boring and ball-end milling the achievable figure accuracy strongly depends on the geometry of the cutting edge and on tool alignment. Up to now, tool alignment is performed with available standard precision components. However, when large tool radii and/or high rotational speeds are employed, the limited stiffness and imbalance of tool holder designs based on such components eventually leads to chatter and process instability [3].
In this paper the development of a novel ultraprecision tool alignment setup is shown and first machining results are presented.

Introduction
Contour boring is performed by infeeding a rotating half-arc monocrystalline diamond tool along the axis of rotation. The contour of the cutting edge is directly copied into the surface. Ball-end milling is realized by superimposing the rotational motion with a lateral feed motion (fig 1.).

Fig. 1: Contour boring and ball-end milling with half-arc monocrystalline diamond tools.

The achievable figure accuracy depends on the geometry of the cutting edge and on tool alignment. The vertex of the cutting edge must precisely be aligned to coincide with the spindle axis. Moreover, the angular orientation of the diamond tool with respect to the spindle axis has to be aligned in order to avoid ogive shapes of the machined cavity. Fig. 2 shows this type of misalignment and the resulting contour errors.
First tool alignment experiments were performed with a standard precision linear-slide, a rotary table and a spherical bearing for tilt adjustment (fig. 3). The position of the tool vertex was measured with an optical microscope and was aligned by moving the vertex towards the spindle axis by means of the linear slide and rotary table ($\Delta \phi$, $\Delta x'$). Tilt alignment was done by measuring the shape of bored cavities with a white-light interferometer (WLI), calculating the tilt misalignment $\chi$ and correcting the tilt correspondingly. In successive steps of centring, boring and tilt correction a figure accuracy $PV \approx 0.2 \, \mu m$ could be achieved.

Unfortunately, large tool radii, hard workpiece materials and high rotational speeds lead to figure deviations and chatter marks. This is caused by high thrust forces compared to the relatively low stiffness of the alignment setup.

**Novel Tool Alignment Setup**

For overcoming imbalance and stiffness limitations, a novel ultraprecision tool alignment setup was developed. The new setup consists of two moveable ring elements which are arranged in different off-axis positions, such that moving one or the other of these elements does not affect the overall balancing state of the setup. The half-arc diamond tool is clamped in the tilt adjusting device placed in the inner ring element of the setup.
By rotating the respective ring element the tool can be moved in the x/y plane within an area of a few square-millimeters with respect to the rotational axis C with a positional accuracy < 0.2 µm. The movement of each ring element is realized by a pinion gear and a gear rim. High stiffness of the system is guaranteed by using conical ring elements with a 15° cone angle for self-locking. The tilt is adjustable in two degrees of freedom by a spherical guiding device with four differential micrometer screws. Tilt errors can be corrected within a range of +/- 3° with an accuracy < 0.05°. The stiffness is ≈ 25 N/µm, compared to ≈ 5 N/µm for the conventional system. The tool alignment procedure was done in the same way as described above. The balancing state of the setup was monitored with an accelerometer.

Fig. 4: Novel adjustable tool holder (1. outer ring element; 2. inner ring element; 3. tool holder; 4. device for tilt adjustment).

Results
Contour boring and ball-end milling with the novel setup is shown in fig. 5. Spherical cavities were contour bored in an electroless nickel plated steel specimen with half-arc monocrystalline diamond tools with an nose radius $r_ε = 80$ mm. Feed velocities between $v_{FB} = 0.02$ mm/min and 0.5 mm/min and rotational speeds up to $n = 2000$ min$^{-1}$ were employed. For ball end milling a horizontal feed between $v_{FF} = 1.0$ mm/min and 2.5 mm/min was applied. The achieved roughness was $Ra = 4$ nm measured along the flank of the cavity over an area of 0.98 mm x 1.29 mm with an WLI.

Fig. 5: Contour boring and ball-end milling (left: machining setup, right: WLI-image of milled cavity) with the novel tool alignment setup.
Thrust forces were measured with a high resolution force transducer with an operating threshold < 0.01 N. The thrust forces were found to be less than 3 N, essentially free from superimposed vibrations.

Cavities bored with the conventional and the new setup are shown in fig. 6. The figure accuracy obtained with the novel design was $PV \approx 100$ nm compared to $PV \approx 200$ nm with the conventional setup.

![Fig. 6: Bored cavities in electroless nickel with identical machining parameters (left: conventional setup, right: novel setup).](image)

**Conclusion**

The paper shows the design of a novel tool alignment setup for contour boring and ball-end milling and describes the alignment procedure. The vertexes of half-arc diamond tools can be positioned with an accuracy < 0.2 µm in the x/y plane. The angular orientation is adjustable with an accuracy < 0.05°. The advantages of the new setup are higher stiffness and excellence balancing independent of the actual tool position. Therefore, high rotational speeds up to 2000 min$^{-1}$ can be applied in contour boring and ball-end milling with tool nose radii up to 80 mm.

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**References**