Diamond Flycutting Machine for Producing Flat Surfaces on Half-Meter Scale Diamond-Turnable Optics

Richard C. Montesanti, Stanley F. Locke, and Samuel L. Thompson

Lawrence Livermore National Laboratory (LLNL)
Livermore, CA 94551
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Overview

A diamond flycutting machine for producing flat surfaces on half-meter scale diamond-turnable optics was designed, built, and tested at LLNL. The machine can accommodate surfaces as large as 490 mm x 490 mm, and has a vertical positioning range of 100 mm. A new LLNL vertical stage supports the workpiece and provides elevation, orientation, and depth-of-cut control, allowing the use of a fixed-position vertical-axis flycutter. The vertical stage has 100 mm of travel, a depth-of-cut accuracy of ± 25 nm, and an average stiffness in all three directions of at least 13 N/μm (14 μin/lb compliance). It also provides tip and tilt angle adjustments of +/- 0.25° with 0.2 μrad accuracy. Designed to function as a stand-alone system, the LLNL vertical stage can be easily used on other precision machine tools.

Supporting an effort by the NIF project to use equipment already within the DOE complex, the diamond flycutting machine uses a surplus Moore #5 Jig Boring Machine. (See Figure 1) The #5 Machine was stripped down to the base and upright columns. The X-axis slideway (double-vee with roller bearings), servomotor, and Moore leadscrew were retained. The existing geometry of the X-axis slideway met our requirements (measured values of 0.33 μm vertical straightness of travel and 0.25 arcsec of roll in the workzone). New hardware for the machine includes the vertical stage and its metrology system, bridge, motorized air-bearing spindle, flycutter, spindle brake, machine controller, and user interface. (See Figure 2) This paper will describe the development of the machine, and the key elements of the design.

Referred to as the “Prototype Flatness Machine”, it is a prototype for the production machines needed for fabricating the Potassium Di-hydrogen Phosphate (KDP) crystalline optics for the National Ignition Facility (NIF). The machines will be used to generate flat surfaces on 410 mm x 410 mm KDP plates, and orient those surfaces to the crystallographic axis. The specifications for the surfaces produced by the machine are 1.6 μm flatness with 0.3 μm repeatability, 12 nm rms roughness, and 5 μrad orientation accuracy. (12 nm rms is sufficient to allow optical testing of the surface. A different but related machine is used to produce a final surface finish of 3 nm rms.) The approximately 600 crystals will be used as Pockels cells (polarization rotating devices) and laser-light frequency doublers and triplers. The NIF is planned to be the world’s most powerful laser system, with a design goal of achieving nuclear fusion ignition and moderate gain.

In June 1999 the Prototype Flatness Machine produced two 410 mm x 410 mm surfaces on a 100 mm thick aluminum part. The first surface had a flatness of 0.8 μm and a roughness of 10 nm rms. The part was then re-machined, producing a second surface with a flatness of 1.0 μm and an average roughness of 10 nm rms (8 – 13 nm rms range over nine locations). Approximately 50% of the flatness errors are due to room air temperature fluctuations during the final machining passes. (The prototype machine does not yet have a temperature-controlled oil shower, machine enclosure, or air isolators.) The vertical stage demonstrated angle adjustment accuracy within 0.2 μrad.

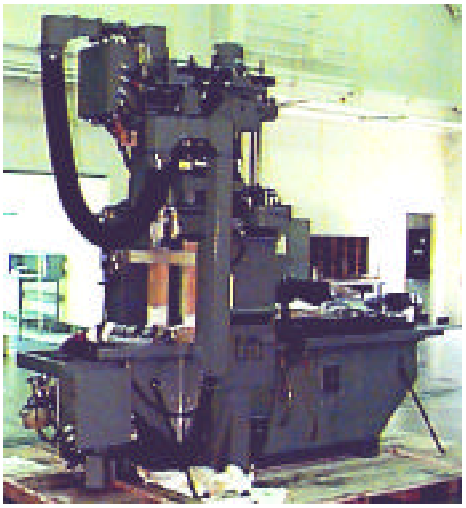

Figure 1: Moore #5 Jig Borer

Figure 2: LLNL Prototype Flatness Machine (with workpiece)

Description of the Machine

A bridge supports a vertical-axis spindle and flycutter over a horizontal-axis slide. Mounted to the horizontal slide is a vertical stage that provides elevation and orientation control of the workpiece. The surface to be machined lays in a horizontal plane. The vertical stage is made up of a workpiece platform supported by a three-vee kinematic mount on three independent vertical-axis linear slideways. (See Figure 3) Three laser linear interferometers are used to measure the vertical position and orientation of the platform. The measurement beam for each interferometer is near and runs parallel to the vertical slide that predominantly depends on it. A laser-based metrology system was chosen because the tip and tilt rotations of the platform (and the associated in-plane rotation and translation motions) do not significantly effect its performance. Optical linear scales were considered, but they require special mounting hardware or master-slave slide systems. (Interferometers and optical scales both require sealing against debris and oil, and since the cost of the purchased components was comparable, the tip and tilt effects drove the decision towards the laser system.)

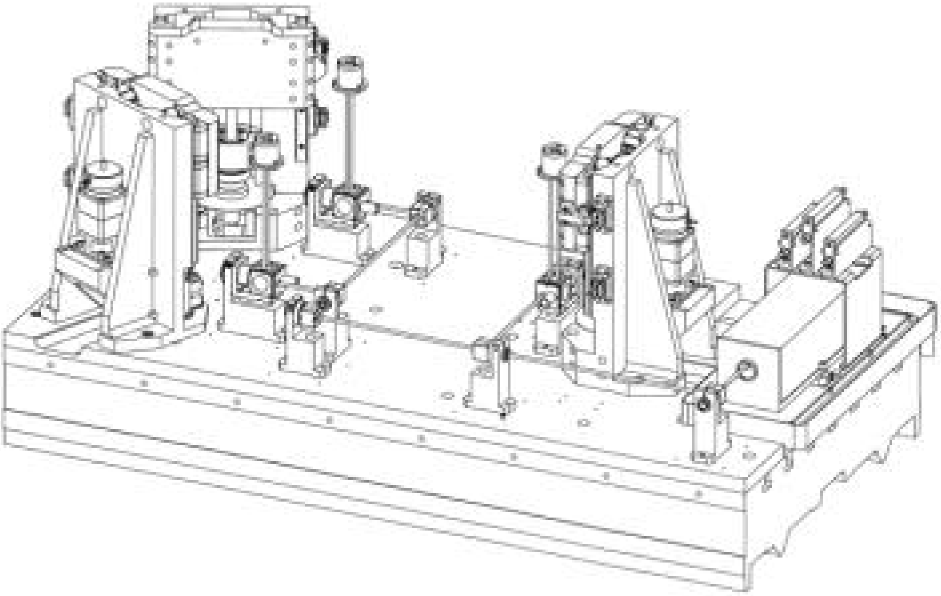

Figure 3: Vertical Stage (platform removed)

The accuracy requirement for spindle squareness drove the decision to fix the spindle to the bridge. A 1 arcsec squareness error between the spindle axis and the horizontal-slide travel produces a 0.7 μm flatness error in the workpiece, so a spindle slideway would need sub-arcsec angular motion accuracy. (In contrast, orientation errors of the workpiece do not create flatness errors.) Mounting the spindle to the bridge with front-to-back and left-to-right symmetry has a number of advantages over a more common arrangement of cantilevering it from the front of the bridge. Heat from the spindle bearing and motor create a symmetrical temperature profile in the bridge when the spindle is centered, reducing squareness errors caused by thermal distortion of the bridge. Centering the spindle in the bridge also provides a stiffer structural loop between the tool and workpiece, and a lower rotational inertia about the long axis of the bridge (the first leads to a better surface finish, both combine for a higher first natural frequency). Locating a sub-arcsec spindle slideway in the center of the bridge appeared formidable. Cantilevering it from the front of the bridge, and dealing with the stiffness, inertia, and thermal sensitivity issues appeared to be a brute-force approach. By fixing the spindle symmetrically within the bridge, we gained the advantages described above, and narrowed the critical design effort to one aspect of the machine, the vertical stage.

All of the other subsystems involve proven technology or straightforward machine design practices. The bridge is a steel weldment with a closed section and internal gussets to provide high torsional and bending stiffness. It sits on three adjusting screws that allow alignment of the spindle axis to the horizontal-slide travel. One of the screws has a differential thread for providing sub-arcsec roll adjustment of the bridge. The bridge is currently held down by eight bolts on each end, but has provisions to be grouted to the columns for increased stiffness and temporal stability of the alignment (if needed). The flycutter has a lightweighted conical-shaped aluminum body with a constrained-layer-damping back cover (similar to an earlier flycutter built by LLNL for an older related machine). An annular reservoir built into the top of the flycutter is provided for feeding workpiece coolant to the tools by centrifugal force though internal passages. The flycutter has provision for four tool holders that are staggered radially from each other to allow multiple-tool machining of a workpiece. The toolholders mount to the flycutter in a semi-kinematic fashion that provides both high stiffness and repeatability of depth-of-cut location (allowing off-machine tool setting). The spindle is a Professional Instruments motorized 10R air bearing. Similar spindles have being used on related machines at LLNL with great success (the LLNL “Small KDP Machine” routinely produces 1.5 – 2.0 nm rms surfaces on 50 mm x 50 mm KDP samples). The machine controller is based on an IBM PC platform using a Windows NT operating system and a Delta Tau PMAC2 controller card. The control software and user interface for coordinated motion of the vertical stage and X-axis slide were created at LLNL using the PMAC and Java programming languages.

The Vertical Stage (Patent Pending)

The vertical stage represents the enabling technology for this machine. It supports the workpiece and provides elevation, orientation, and depth-of-cut control. The underside of the workpiece platform has three vees that open down. Each of the three vertical slides functions as a “ball” that engages a vee. Together, the system behaves exactly as the well known three ball-and-vee coupling. (See Figure 4) Elevation and orientation is accomplished by providing each “ball” with an independent vertical translation. Consider the following evolution of a ball into one of the vertical slides. (See Figure 5) The normal contact forces (N) acting on a ball from its vee are directed through the center of the ball. Therefore it is desirable to support each ball at its center so that the normal contact forces do not generate an overturning moment (Figure 5a). Any tangential contact force will rotate the ball about its center, but not move the center. In Figure 5b, a hole through the ball allows it to be supported at its center by a vertical-axis ballnut (the centerline of the ballnut and its ballscrew lay in the same plane as the normal contact forces (N) on the ball). In Figure 5c, a vertical-axis linear guide is added to both sides of the ball (both guides lay in the same plane as the normal contact forces). In Figure 5d, the vertical slide is completed by removing the portions of the ball that do not contact the vee or are not needed for other purposes.

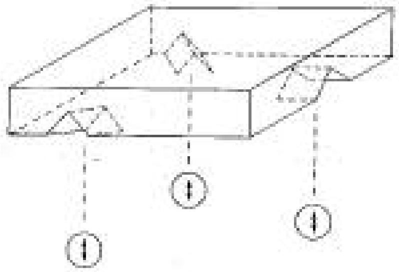

Figure 4: Three ball-and-vee coupling

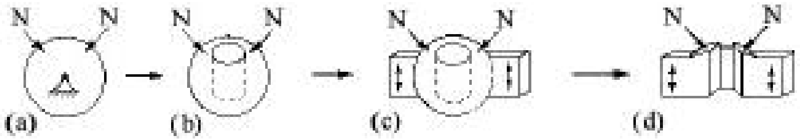

Figure 5: Evolution of a ball into a vertical slide

Figure 6 shows the critical load carrying elements of the three vertical slides (arranged to match the three vees in the underside of the workpiece platform). Consider the slide on the right. The normal contact forces (N) on this “ball” from its vee act upon two small sections of a sphere (having a common center with the ballnut), and develop a force at the center of the ballnut. The vertical component of the force at the center of the ballnut passes straight down the centerline of the ballscrew and is balanced by a vertical force (V1, shown in two pieces) on the thrust bearing that supports it. A piezoelectric actuator (PZT) that is described later also develops a vertical force on the end of the ballscrew (V2, shown as the force supporting the PZT). The horizontal component of the force at the center of the ballnut is balanced by forces (H) developed by two pairs of recirculating-ball linear bearings. For each vertical slideway the normal contact forces (N), ballnut, ballscrew, and linear bearings all lay in a common vertical plane, so there are no overturning moments in the system. (Tip and tilt motions of the workpiece platform cause the normal contact forces (N) to move slightly out of the plane of the load carrying hardware, but the effects are negligible for the small angles involved.)

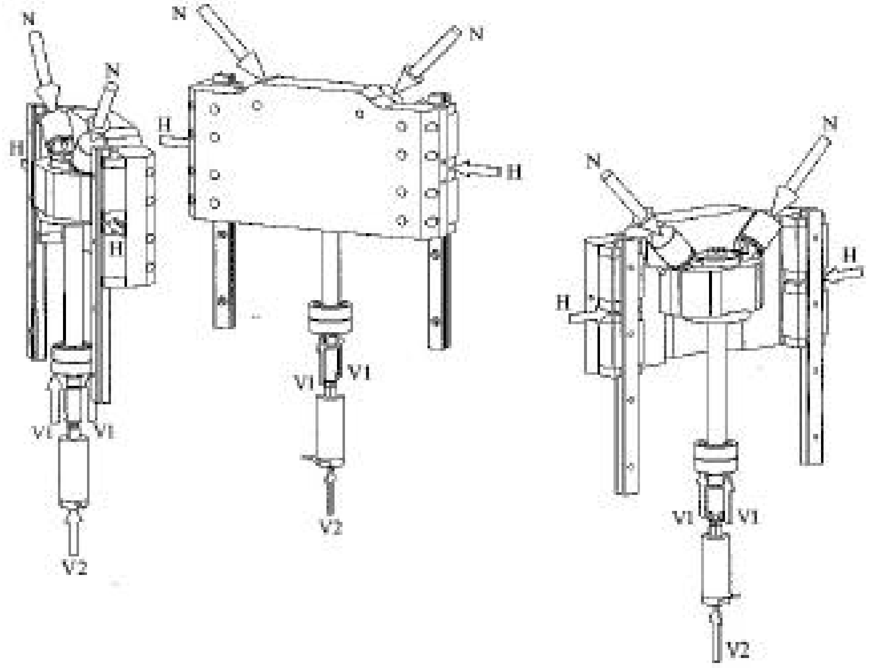

Figure 6: Load carrying elements of the three vertical slides

Note that as with the classic ball-and-vee coupling, horizontal forces along the vee are not restrained (towards the center of the platform). Tangential contact forces (not shown) on the spherical sections will tend to rotate the vertical slide around the center of the ballnut, and to first-order not