This paper describes a four cup lapping machine for finishing balls of 40 mm diameter to a roundness of $10^{-6}$ diameters or better. The spring loaded lapping cups are spaced tetrahedrally for maximum size and uniform distribution over the ball surface. A four cam control mechanism switches the sense of rotation of the four lapping motors in such a way that the ball rotates about a different axis at each switching. This achieves good uniformity in lapping action. Motor rotation combinations which would produce a ball rotation in or near to a cup axis are avoided. Lapping tests have produced roundness of $25 \times 10^{-6}$ mm.

The four cup lapping machine (Fig 1) must produce in a reasonable time small quantities of extremely high precision balls. The current requirement is for a 38.1 mm diameter fused silica sphere to be used as a flywheel for a gyroscope. The roundness of this sphere is supposed to be as good as possible, but not worse than $25 \times 10^{-6}$ mm. The surface finish must have optical quality and be free of any imperfection.

Another application for high precision spheres is for measuring the density of certain materials to extremely high accuracy. The spherical shape was selected because, having measured the diameter of a high precision sphere, its volume can be calculated to the same degree of precision.

Also, gauge balls of extreme precision are needed to check the roundness quality of the spindle bearing performance for measuring and testing equipment.

**History**

Ball-lapping devices have been made for a long time. It is said that, thousands of years ago, the Chinese made beautiful balls of indish ivory by carving them round with primitive tools and finishing them at the square ends of one or two sticks of bamboo.

We have manufactured sophisticated ball-lapping machines of different types and sizes. The largest was for a 250 mm ball of aluminium. The ball and its floating cap, which was also finished in the same machine, were used as an airbearing for a space simulator with three degrees of rotational freedom and a load capacity of over one ton.

With another polishing machine we have also made spheres for the National Bureau of Standards, Washington, DC. These are 63.5 mm in diameter and are made of opaque fused silica to be used to define the precise density of the material. The spherical shape was selected because the volume of a sphere can be more closely measured than the volume of any other geometric form.

Our present effort is, and has been for some time, to make 38.1 mm diameter spherical gyro rotors of fused clear quartz to be used for the Schiff relativity experiment, conceived and under development at the Stanford University in California (see *Precision Engineering*, January 1979, 1(1) 5-11). Certain phases of this NASA project (Gravity Probe B) are being developed at the George C. Marshall Center and at the University of Alabama in Huntsville.

**Problem areas**

The quartz should be free of stress to the limitation of current measuring capability, because stress-non-uniformity will, in time, relax and cause changes in roundness. Fused silica has very high dimensional stability when it is totally free of stress. There may be residual stress from stress-relieving or new stress introduced by machining (cutting, grinding). Local stresses can best be seen by placing a cube of...
quartz with all its six sides finished to optical flatness between a polariser and analyser in a simple test set up. Stress changes the optical index of refraction which causes changes of light intensities. The insertion of a quarter lambda film intensifies the image of the stress irregularities. For quantitative measurements of the index of refraction a refractometer should be used or interferometric methods applied.

Surface stress can be removed by chemical etching with hydrofluoric acid and internal stresses only by annealing. Suppliers of quartz list the index of refraction for better grades to six digits eg 1.455818 at 20°C, 0.68 µm wavelength and at 760 mm Hg.

Accurate diameter and roundness measurements to 1 part per 100 000 and 1 part in ten million, respectively, were made by the latest Talyrond machine.

The overriding problem in the past has been the intelligent control of the lapping machine to produce, in an acceptable time, the required roundness of the ball. Furthermore, it was difficult to accomplish roundness before the right diameter was reached unless one started with a ball greatly oversize, which meant long periods of lapping and polishing.

It was obvious that a much more efficient finishing method was needed. A careful investigation of the lapping cup arrangement, the actions of the lapping cups and the ball motions brought better understanding of the lapping problem and resulted in a new control mechanism for the lapping machine.

Design options
Several design options for the machine were studied. Arrangements using two to six cups were drafted and finally the four cup tetrahedral design was selected. The use of automatic motor reversing control, dust protection, temperature regulation and the selection of stress free quartz as ball material is vital for accomplishing a roundness accuracy of one in ten million.

The tetrahedral finishing machine
The machine (Fig 2) has four reduction gear reversible dc motors, arranged tetrahedrally, with angles of 109.47° between their shafts. The output shaft of each rotor has an axially floating universal joint, carrying the lapping cup and the axes of the shafts intersect at the tetrahedron centre. The output shaft of the three lower motors B, C and D are spaced 120°, when viewed from above, and tilted upward 19.47°. The shaft of the upper motor A is pointing straight down to the centre of the three lower shafts. The forces of the cups must be balanced to hold the ball in the centre of the tetrahedron. The universal joints minimise possible lateral forces of the cups caused by varying lapping friction.

The lapping cup diameter should be as large as possible (0.8 times ball-diameter) because larger cups, near the ball diameter, have a much better chance of making the ball round. It is important that the cups keep the ball moving at all times. This can be accomplished by changing the sense of rotation of the cups, at short time intervals, in a certain pattern. Since visual observation of the ball movements is practically impossible, nor is it possible to know which way the ball drifting should go with time, proper hand control of the four cup motors cannot be accomplished. An automatic device was therefore developed to accomplish the optimum roundness in the minimum time.

Polishing compound application
The polishing machine, like commercial flat lapping machines, has a metering polishing compound dispenser. A fifth cam in the motor control box opens and closes a valve for the polishing compound flow. Manual compound application is undesirable because of its inherent irregularities.

Dust and temperature control
The machine is protected by an enclosure (Fig 1) against dust, air draughts and sudden temperature changes. In addition the machine is located in a ±1° temperature controlled room with clean room conditions. This is an advantage for polishing and essential for measuring diameter and roundness.

Ball motion control
The ball is supported and rotated by the four lapping cups which can be individually controlled to turn right or left. The speed range of the cups is somewhat limited by poor lapping efficiency at low speed and by the throwing off of the lapping compound at high speed. It was found from experience that a speed of 100 - 120 rev/min works well. Controlled speed variation was not needed and therefore not used, which simplified the control mechanism.

Efforts were made to find a series of rotation combinations for the four motors driving the lapping cups to cover most uniformly over time the entire ball surface. Having four cups,
each of which can rotate right or left, gives \(2^4 = 16\) possible combinations (see Fig 3 and Table 1; where R and L stand for Right and Left hand rotation of the cups).

Combinations 1 (LLLL) and 2 (RRRR) produce no motion of the ball. This can be explained as follows: assume the top lapping cup A is removed. The cups B, C and D turning all in the same direction (clockwise) will produce a vertical spin vector of the ball with a value of unity which is equal to the geometric sum of the individual cup vectors of B, C and D. By adding cup A with its vector ‘one’ in the vertical position but in the opposite direction will cancel the ball vector B, C and D and the ball will not move. Then, each of the four cups would wear a ring groove into the ball surface. Thus, the combinations 1 and 2 must be eliminated.

Combinations 3 to 10 produce ball rotations about the axis of one of the cups. For example, in combination 3 (RLLL) the cups B, C and D produce a ball motion about axis A, and in the same direction as cup A; therefore, there is no lapping action under cup A.

The third and last group of combinations, 11 to 16, produces ball motions which give the desired lapping actions. For example, in combination 11 (LLRR) cups A and B together cause a ball rotation about the centre of the A and B axis (called the K axis). Cup C and D would turn the ball about the centre of the C and D axis, which is the G axis.

<table>
<thead>
<tr>
<th>Group</th>
<th>Combination</th>
<th>Ball旋转</th>
<th>Cup rotations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1 L L L L</td>
<td>-</td>
<td>A B C D spin axis</td>
</tr>
<tr>
<td></td>
<td>2 R R R R</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 R L L L A</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 L R R R A</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 L R L L B</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 R L R R B</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>7 L L R L C</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 R R L R C</td>
<td>L</td>
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<tr>
<td></td>
<td>9 L L L R D</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 R R R L D</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11 L R L R G</td>
<td>R</td>
<td>K L</td>
</tr>
<tr>
<td></td>
<td>12 R R L L K</td>
<td>L</td>
<td>R - G L</td>
</tr>
<tr>
<td></td>
<td>13 L R R L H</td>
<td>R</td>
<td>R - H L</td>
</tr>
<tr>
<td></td>
<td>14 R L L L E</td>
<td>L</td>
<td>R - F L</td>
</tr>
<tr>
<td></td>
<td>15 L R R L E</td>
<td>R</td>
<td>R - E L</td>
</tr>
<tr>
<td></td>
<td>16 R R L R E</td>
<td>L</td>
<td></td>
</tr>
</tbody>
</table>

*R = right; L = left

Because of the tetrahedron geometry, the K and G axes are identical. Figures 3 and 4 show four cam controls.

The torques of all cups are added in the K-G axes, and the ball rotates. The coverage of the ball by the cups is not 100% nor is it uniform. A small area at the entrance of the K and G axes is not covered because the lapping cups have only 30 mm diameter instead of the theoretical value of 31 mm (ball radius = 19 mm; angle between A and B = 109.5°; thus maximum cup diameter = \(2 \times (\sin 109.5/2) \times 19 = 31\) mm). The small circular area between the cup edges will only be covered as the ball spin axis changes, which happens every 10 s. In practice, the ball axis moves all the time because the friction of the cups is never constant.

The speed of the ball rotation and the drifting rate of the ball spin axis are strongly dependent upon the friction of the lapping cups which changes with the cup condition, compound consistency and amount. The motion of the ball is the result of cam control and varying friction. The efficiency of the lapping operation also depends on the care of the pitch laps.

Lapping operation
The rough shape of the quartz ball is produced with a curve generator. This machine has two spindles which can be set to an angle to each other. The tool spindle has at its end a cup wheel impregnated with cutting diamonds. The other spindle holds the workpiece to be cut. The spindles rotate in opposite directions; the cup wheel cuts with its inner edge when making convex spheres, the outer edge generates concave spheres. The resulting curvature is given by:

\[
\sin \alpha = \frac{\text{cup diameter}}{\text{ball diameter}}
\]

In one setting only a partial sphere can be made. For completion, reset the ball into a ball chuck, cut the stem, and finish that side.

The cutting rate should be very low using a fine grain wheel especially when approaching the final dimension, leaving about 0.5 mm stock to be removed by lapping and polishing. Lapping is performed in the four cup
tetrahedron lapping machine, using brass cups, aluminium oxide of various grit sizes, and water. The cutting medium is not bonded but loosely rolling between the brass and quartz surfaces. Water is used to carry the grit, to wash away the abraded material and, to some degree, for cooling. Roundness can be achieved very early by keeping the abrasive layer thin (if possible, 1 grit particle size thick) so the cup has maximum efficiency and does not tend to tilt and cause uneven lapping action. The grit should be changed to finer sizes, 600 to 1200, as the stock is being reduced to 0.05 mm.

**Polishing with pitch laps**

The pitch must be strained to be free of foreign particles which cause scratches and should be soft to form well to the sphere and to imbed polishing grit, yet should not have excessive cold flow. Cold flow can be reduced by keeping the room temperature at a low level, 16 to 18°C, and the lapping cups survive longer at these temperatures.

The lapping cup is cut free at the inside to about 50% of its diameter. For lapping larger spheres, the lapping cup surface should have criss-crossing grooves for easier flow of material. The outside diameter of the cup can be held by a paper cylinder to restrict cold flow; this cylinder is also helpful in casting the cup. The cast cup should be aged for a day or so before using it. In addition to the criss-crossed grooves, the centre of the cup should be well vented by a hole to one side. During the finishing operation with cerium oxide and water, the abrasive film at the ball surface should be uniform in appearance without streaks or visible markings. Such streaks and markings indicate an uneven polishing action and can cause defects. The total polishing time of a 40 mm ball with a pitch lap should be not more than 5 h for a roundness of $25 \times 10^{-6}$ mm. For roundness measurements to at least $25 \times 10^{-6}$ mm accuracy a Talyrond is used at its highest magnification and with spindle error compensation (see Siddall G.J. and Lipa J. Precision Measurement of Gyro Rotor Sphericity, Precision Engineering, July 1980, 2(3), 123–128).

**Lapping cup alignment**

For uniform lapping force along the periphery of the cup it is essential to have good alignment of drive shaft, cup and ball centre. The quality of the alignment can be seen by observing the gap size between the cups at the ball surface. A convenient aid is a microscope with a long working distance and a templet (reticule) in its eye piece focal plane. The templet shows three equal gaps which can easily be compared with the actual gaps. Another indication of non uniform force are streaks or non-uniform films of lapping compound at the ball surface.

**Results and recommendations**

The four cup tetrahedron ball finishing machine with a directional control device for the cup motors has produced balls with roundness better than one millionth of the ball diameter in less than 8 h. The basic points for design and operation of the machine are:

- The cups should be as large in diameter as possible (80% of the ball diameter)
- The cups should be well vented and the lapping surface cross-grooved
- All four cup axes must at all times be well aligned with their drive shafts and point exactly to the ball centre
- A lateral cup support should be provided to eliminate shifting of cup position by lapping friction. (This feature is not yet introduced to the present machine)
- The ball should always be in rotation and frequently, every 5 to 10 s, change its spin axis; or better the spin axis must continuously precess.
- The spin axis of the ball must never be in line or nearly in line with a cup axis, other than momentarily

Strict conformance with these basic concepts produces more accurate balls in much shorter time.

**Acknowledgement**

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