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PRODUCTION OF FLAT OPTICAL ELEMENTS FOR MILLIMETRE AND SUBMILLIMETRE RANGES ON COMMERCIAL NUMERICALLY CONTROLLED MACHINES

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Abstract—Consideration is given to the issues arising in the production of flat optical elements for millimetre and submillimetre ranges on commercial industrial machines with numerical control. A method for the production of flat optical elements on a numerically controlled turning machine is described, together with the appropriate algorithm. Much attention is paid to the technical details of making a cylindrical lens on a numerically controlled milling machine. Methods enabling the production of flat optical elements with specified accuracy on such a machine are described, as well as algorithms for control programs. The flat optical elements produced by these methods on commercial numerically controlled machines are briefly described.

Flat optical elements operating in the millimetre and submillimetre ranges may be manufactured on numerically controlled (NC) machines normally available in mechanical engineering. Circular elements can be produced relatively simply on lathes, and cylindrical elements on milling machines. More complicated shapes can be made on milling machines with automated platforms possessing 5–6 degrees of freedom.

In machine construction the movement of the instrument with respect to the part, from the initial to the final working point, may be accomplished in three ways.

(1) In the simplest system, by successive movement along each coordinate, for example, first along z and then along the x-axis.
(2) Along a direct straight line motion from the initial to the final point.
(3) Along a preprogrammed circular arc.

Movement of the instrument in a lathe, or of the part in a milling machine, is carried out by a step-by-step mechanism. A single step determines the size of the discrete coordinate grid at whose sites the point instrument may be in static state. The mesh size determines the precision of the manufacturing process. In linear or circular interpolation the trajectory of the instrument traverses a path approximating the specified one in terms of the grid sites, spaced as though they were elementary sections of the path. For each elementary section the rule in going from the initial to the final coordinate is fixed by a constant drive-time along each axis, and while keeping the drive monotonic one can depart from a linear law by a simultaneous operation along some of the axes.

The mean site in modern machines is around 5–10 μm, although 1 μm machines have already been advertised.

The surfaces of flat optical elements cannot normally be described in terms of a linear or circular cut, so that the programming of the instrument motion relative to the product along the complex trajectory proceeds by way of a piecewise-linear approximation which takes into account admissible tolerances.

For simplicity of discussion, we shall consider the tool to be moving with respect to a stationary product, even though the reverse may exist in some machines.

One should distinguish errors generated by the discrete coordinate grid of the machine from errors acknowledged *a priori* as negligible in the production process of the element. A lowering of the precision requirements in the production of an element considerably reduces the control programme and accelerates its execution.

The accuracy of the surface is determined by the instrument profile and by the size of the interval between two neighbouring trajectories. The instrument profile is fixed by the sharpest slope between the neighbouring trajectories. In lathe work the distance between two neighbouring trajectories is determined by the feed of a single revolution, and may be taken to be quite small. In milling machine production each new pass of the tool over the work surface is performed in response to

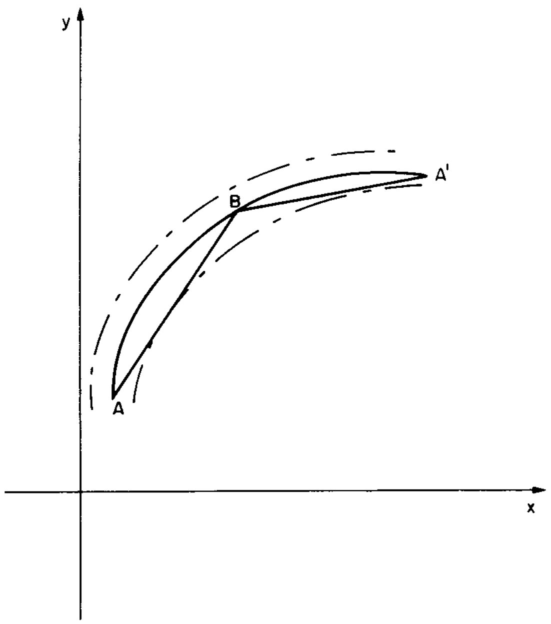

Fig. 1.

certain machine commands, each of which is represented on the control tape by one frame. If the distance between neighbouring passes is small, very long control programmes will be required.

The following algorithm was employed in preparing the control programme for lathe production of flat optical elements:

(1) The exact values of the element profile coordinates were calculated in accordance with the specified equation.

(2) A tube was generated around the computed profile of the element with a radius equal to the admissible tolerance (see Fig. 1).

(3) Starting from the zero (initial) point the coordinate of the running point on the profile was calculated in such a way that the straight line joining the initial and the current points did not cross outside the tube, while maximizing the distances between the two points.

(4) A machine instruction was formulated to move the instrument on the path from the initial to the current point. The command was stored as a sub-routine.

(5) The coordinates of the current point replaced those of the initial point and the sub-routine was repeated until the whole profile of the element was covered.

(6) The sub-routine was added to the main control programme.

The control programme for element production was run several times in order to observe cutting-technology norms (thickness of shavings, feed rate, revolutions).

Cylindrical lenses possessing complex profiles were produced on an NC-470 milling machine made in the GDR. This machine performed synchronous motion along only one of three coordinates. The machine's minimal finishing distance was 0.01 mm. Problems in lens production arose in the initial stages. The first complication encountered involved choice of the cutting tool. Figure 2(a) illustrates the section of the lens which is most problematic in NC milling machine production. If one uses a mill with the smallest possible diameter, then section B will not be covered and its milling will turn out to be more complicated than the original specification. So the cutter of choice was a tool having a precalculated profile, and the milling machine was used in a planing mode (Fig. 2b).

Employing the machine in the planing mode implies that the cutter is in a strictly fixed position, i.e. the machine operates with a slowed down spindle. But such an operating regime is possible only in fast feed. In the absence of this restriction the problem would be solved by simply providing for the control programme the coordinates which specify the movements along the x, y, z axes. Fast feed imposes a limit on the minimal distance worked by the NC machine. For the NC-470

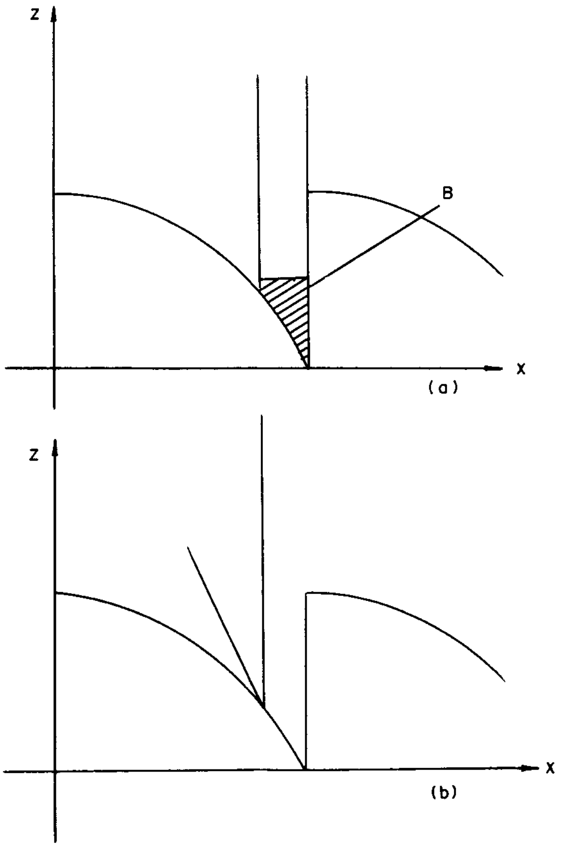

Fig. 2.

model this minimum distance is 13 mm along the x and y axes, and 6 mm along the z-axis. If one were to attempt to simply assign the corresponding coordinates, then an increase in the minimal distance over which the NC operates would lead, for a tool movement of 0.01 mm, to its being deflected to the side by more than 13 mm along the x or y axis, and more than 6 mm along the z-axis. This would imply a significant increase in the number of controlling frames and, correspondingly, in the time taken for the work.

The continuous operating time of an NC machine is normally determined by the working hours of the machine operator and is therefore no more than 8–10 hours per day. This means that the control programme should not run for longer than this, and although the machine remembers the "zero" after being shut off, it is desirable not to depend upon this in case of possible jerking of the machine. Moreover, if the programme were to stop at an arbitrary frame, then after shutting off and restarting the machine it would be very difficult to locate the coordinate of the given frame. To overcome this difficulty, the overall controlling programme would have to be divided into several programmes running less than 8–10 hours, each working on a particular section of the lens.

Apart from the operating features described above, it is important to specify the machine's working space. In the NC-470 model this is 1500 x 350 mm along the x, y axes, so that lenses whose dimensions are 500 x 500 mm cannot be produced in a single cycle. To overcome this difficulty the manufacturing process is carried out in several stages, each of which corresponds to a complete cycle of finishing a predetermined zone of the lens. In a given particular case two control programmes were operated: the first one controlled production of odd-numbered zones from the 3rd to the 11th, the second—even zones from the 4th to the 10th, and also the positive 1st and 2nd zones. The corresponding first programme comprised around 2500 frames and lasted some 5 hours, the second one contained some 3500 frames with a duration of 8 hours. The surface of the processed lens was divided into two symmetrical halves and was prepared by successive machining of the parts, reversing the intermediate product through 180°.

Figure 3 explains the principle of lens production on the NC machine. The basic idea of the

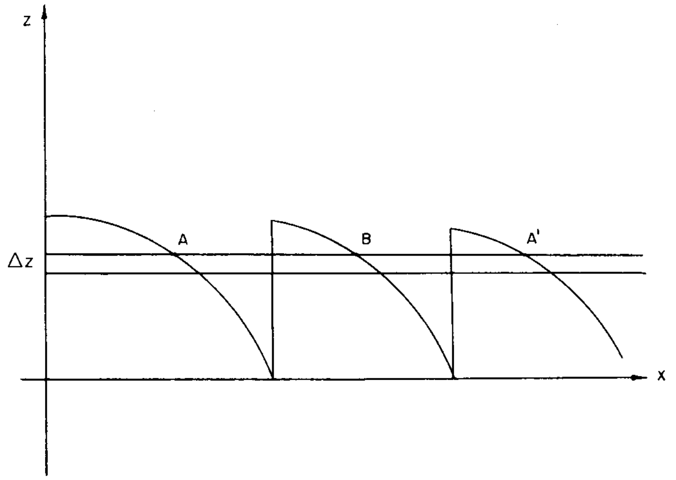

Fig. 3.

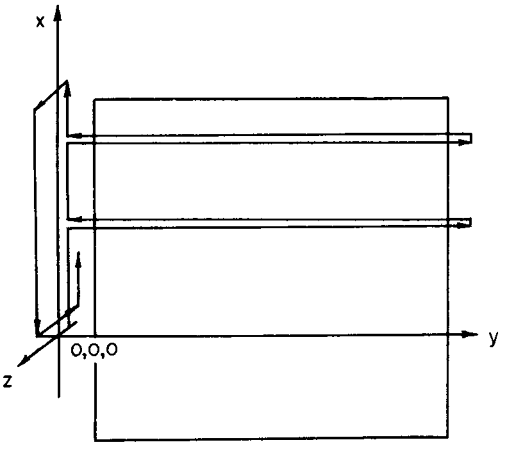

Fig. 4.

method is the uniform deepening of the cutting tool along the z axis by jumps of size Δz. The size of the quantum jump is chosen to satisfy $\Delta z < \Delta H$, where H is the maximal admissible error in the deviation of the real lens profile from the computed value. The size of the actual control shift is found by trial-and-error, using the condition $\Delta z < \Delta H$, while minimizing the number of frames in the control programme.

The cutting tool path is shown in Fig. 4. In the first state one fixes the initial point, which subsequently serves as the zero, i.e. for which $x, y, z = 0$. This is done by manually dividing the surface of the work into two equal parts and scratching a fiducial line along the y-axis which serves as a visual reference. The tool is set just below the upper surface of the lens (to exclude irregularities) and is shifted along the y-axis from the lens edge by a distance of 1–5 cm. After all these operations the machine is "zero-adjusted", the zero coordinate serving as its "zero". The cutting tool motion along the x-axis proceeds parallel to the edge of the lens. Cutting is carried out at specified points, the tool moving along the y-axis first in the positive direction to a specified distance and then reverting to the starting position. Having completed its task along the x and y-axes, the machine moves the tool along the z-axis in the positive direction by more than 13 mm, after which the cutting tool returns to the $x, y = 0$ point and is lowered to a new depth.

The motion of the tool along the z-axis begins from the point at which the lens profile function $E(k, x)$ is a maximum, and proceeds to points which are obtained in the course of successive subtractions of Δz. To locate the tool at a particular point on the axis each zone is successively explored and the result of this scan determines whether cutting of this or that zone is required.

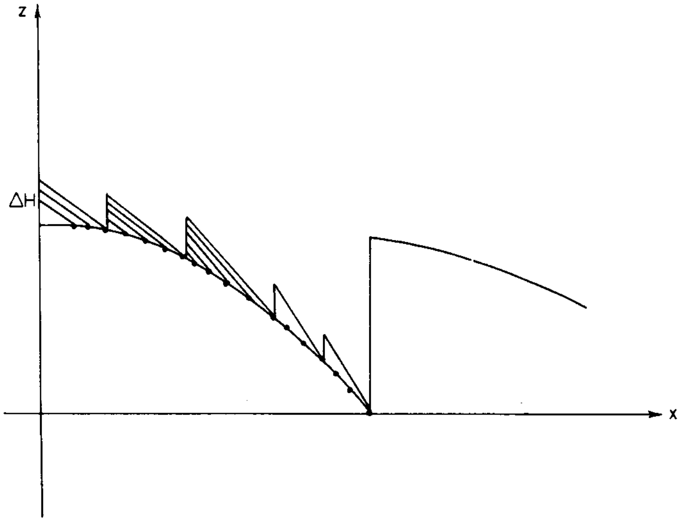

Fig. 5

The determination of the error between points of quantization of the z-axis and the nearest points of the calculated profile enters into the investigation of the zones. In the present case three kinds of deviation are possible: in the first, a single point of the computed profile is situated on the quantized section's boundaries; in the second, several computed points are positioned there; in the third, none of the computed profile points are on the boundaries. The first case is the simplest: one decides to proceed with the cutting. In the second case an error analysis is carried out at each point lying in the specified quantized section, and cutting will be performed at selected points in which the error is a maximum but less than the allowed value. In the third case, before taking the decision not to cut at a particular point, an error analysis is performed between the previous cutting point and the probable point in the following quantized section. If the error is larger than the tolerance value one proceeds with the cutting, otherwise not.

Thus the cutting tool moves along successive quantum jumps along the axis, and at each level is displaced along the x-axis from the first zone to succeeding ones, cutting only in zones where the above condition is fulfilled.

To get by the restrictions imposed by the fast feed of the NC machine, the processing of the lens zones by the first method was done by even or odd zones. This regime conformed with the consideration that the distance between neighbouring zones be larger than 13 mm, and the number of control programmes be a minimum.

This method was used to produce the 3rd to 11th zones, while the 1st and 2nd zones were processed by another method. Figure 5 explains the essence of this latter method. Unlike the method used for the 3–11th zones, a simpler procedure is in force here. Moving in the zone along the x-axis, one calculates the error, and the cutting points will be fixed where the error is maximal, but less than the specified value. The drawback of the method is that the number of control programme frames increases sharply, since to move the cutting tool to a neighbouring point it must be displaced along the x and z axes by more than 13 and 6 mm, respectively. The advantage of the method is its simplicity.

The construction of a control programme for manufacturing flat optical elements on an NC milling machine was achieved by the following algorithm:

(1) The lens was designed and the exact value of the coordinates of the element profile was determined in accordance with specified equations. The angle of the maximal slope of the function was calculated in order to compute the exact instrument profile, and the points of maxima and minima were determined.

(2) Transform from the one-dimensional function $E(x)$ describing the lens profile into the two-dimensional $E(k, x)$, where k is the zone number and x is the coordinate along the x-axis; and record the data in a special file used subsequently as the basic operating file.

(3) Determine the order of the manufactured zone, and assign the maximal admissible machining error.

(4) (The start of the groundwork.) Assign the controlling frames along the axes with a specified interval, prepare the logic scheme for implementing the method, locate the cutting point and specify the controlling frames, repeat the logic scheme a specified number of times.

(5) Evaluate the need to produce the 1st and 2nd zones, given the requirement of passing to the next part of the programme, in the reverse case form the final frames and finish the work.

(6) Produce the 1st and 2nd zones of the lens, by the method of Fig. 5; specify the controlling frames.

(7) Complete the work, forming the concluding frames, end the programme.

The final product of the manufacturing process was a flat optical element in the millimetre range. Two lenses were made: one on a lathe, the other on an NC-milling machine. The first lens had a circular section with a 50 cm diameter, the second was a cylindrical lens whose projection was a square with sides 50 cm. In profile both of these lenses were plane on one side, while the other side was a surface satisfying the specified parameters of the optical elements.

The production of flat optical elements in the millimetre range on industrial NC machines encounters, as we have seen, a series of technical problems which have to be overcome with much care. This is why the methods presented in this work are of definite interest and may be useful for the processing and production of such optical elements in the millimetre and submillimetre range on commercial NC machines.