Part 2
Manufacturing techniques

4 Optical processing

The manufacture of any type of quartz resonator can be divided into two phases. In the first phase, traditionally known as *optical* processing because of close similarities with the manufacture of optical components such as lenses, the operations are directed towards the production of crystal blanks of the desired orientation, dimensions, shape and surface finish. The second phase, known variously as *electrical* processing, or simply *finishing*, covers the operations of cleaning, laying down electrodes (usually by vacuum deposition), mounting, adjusting to frequency and sealing. These process steps are described in more detail in the following chapter.

Figure 4.1 shows a flow chart of the main steps involved in the optical processing of thickness mode resonators such as the AT-cut. The steps are:

(1) Orientation of the crystal bar before cutting.
(2) Cutting or sawing the bar into *wafers*.
(3) Rough lapping of the wafers and angle sorting.
(4) Removal of the seed.
(5) Rounding circular blanks (edging rectangular blanks).
(6) Fine lapping
(7) Angle sorting

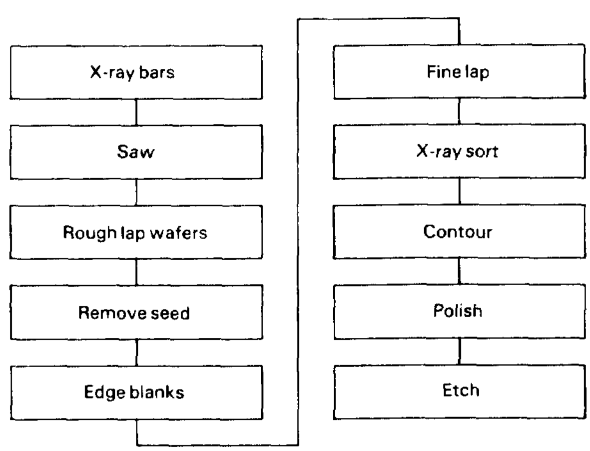

Fig. 4.1 Optical processing steps.

(8) Polishing.
(9) Contouring or bevelling.
(10) Etching.

Depending on the frequency range and performance requirements of the finished resonators, some of these operations may be omitted. The etching process is often physically located in the finishing area, or alternatively in a separate area between optical and finishing shops. Consequently, it is discussed in the following chapter as part of the blank cleaning operation, although strictly speaking it should be included as an optical process since it directly affects both dimensions and surface finish of the crystal blank.

4.1 X-RAY ORIENTATION

For the commonly used AT-cut crystal, tolerances on the angle at which the blank must be cut from the parent crystal are typically of the order of minutes of arc. Increasingly in modern communication systems the frequency stability requirements are such that even tighter tolerances of less than a minute are required. Although in the early days of the industry optical means of orientation were often used, *X-ray diffraction* is now universally adopted as the appropriate technique for achieving the required accuracy.

The physical principles of X-ray diffraction by crystals are the same as those of optical diffraction, with the proviso that in the optical case the wavelengths involved are much longer. In both cases, a beam of radiation is incident upon an array of scattering centres which is periodically arranged in space, and constructive interference between the scattered radiation from the individual elements of the array results in relatively intense scattered or *diffracted* beams in certain directions relative to the array and to the direction of the incident beam. In the optical case, the scattering centres may be the lines of a diffraction grating, whereas in the present case the centres are the individual atoms and molecules of the crystal structure. In either case, the wavelength of the radiation has to be less than or of the order of the spacing of the array elements. For quartz, the unit cell dimensions are approximately 5×10^{-10} m, hence wavelengths of this order are necessary to observe any diffraction phenomena.

If only the angles of the diffracted beams are of interest, rather than their relative intensities, the simple concept of the reflection of X-rays from *atomic planes* in the crystal can be substituted for the more general notion of diffraction. In any crystal, because of its periodic structure, any plane drawn through specific atomic or molecular locations in the crystal will have associated with it an infinite number of similar parallel planes. This family of planes will be characterized by a definite spacing d between successive members. Each plane will intersect the crystallographic axes at certain points, except in the case where the plane is parallel to a particular axis or axes, when the intercepts would be at infinity. If one particular plane that intersects all three axes is chosen as a reference plane, and the intercepts of this *parametral* plane on the axes are taken as units in which to express the intercepts of any other plane, then it is a fundamental law of crystallography (Phillips, 1960) that the reciprocals of the intercepts when so expressed are rational numbers or zero. This is the *law of rational indices*, the reciprocals of the intercepts being the *indices* of the plane in question. Supposing that a given plane has indices (h, k, l), it is clear that the indices (Nh, Nk, Nl) represent a parallel plane, and thus if only the orientation of a family of planes is of interest, it can be represented by a set of three integers obtained by multiplying the indices (h, k, l) of any member of the family by some integer N to clear fractions. When this is done the indices are termed the *Miller* indices of the family of planes, and conventionally written (hkl) without intervening commas. In the case of quartz and other trigonal or hexagonal crystals, it is conventional to use a coordinate system with the Z axis along the trigonal or hexagonal axis, and *three* equivalent X axes labelled X_1, X_2 and X_3 perpendicular to the Z axis rather than the normal X and Y axes. Then the system of Miller indices is modified to the *Bravais–Miller* system using four indices $(hkil)$, where the indices refer respectively to the reciprocals of the intercepts on the X_1, X_2, X_3 and Z axes. However, because all three X axes are coplanar, the first three indices satisfy the identity $h + k + i = 0$, and the Bravais–Miller indices are often written $(hk.l)$ to emphasize this dependence.

The essential ideas of X-ray reflection are first that X-rays are reflected from atomic planes just as light beams are reflected from plane mirrors, that is, with equal angles of incidence and reflection, and second, that *strong* reflections only occur at those angles of incidence such that the reflections from all the planes parallel to the given plane reinforce each other. This condition is expressed in Bragg's law of X-ray reflection

$$2d\sin(\theta) = n\lambda \tag{4.1}$$

where θ is the glancing angle or *Bragg angle*, λ is the wavelength of the X-ray beam, d is the spacing of the atomic planes, and n is an integer. Bragg's law simply expresses the condition that the path difference between reflections from successive planes be an integral number of wavelengths; Fig. 4.2 illustrates the geometry involved.

Equation (4.1) provides the basis for the use of X-rays in determining crystal orientations. The first step is to select an atomic plane which lies parallel or almost parallel to the desired orientation of the major surfaces of the crystal. In the case of the AT-cut the plane normally selected has Bravais–Miller indices (10.1), for which the interplanar spacing is 3.3362 Å. Assuming that the wavelength λ is 1.537395 Å corresponding to the Cu $K\alpha_1$ line, the first order reflection, $n = 1$, occurs at the Bragg angle θ_B of 13° 19′. If now a collimated X-ray source and detector are arranged as in Fig. 4.3,

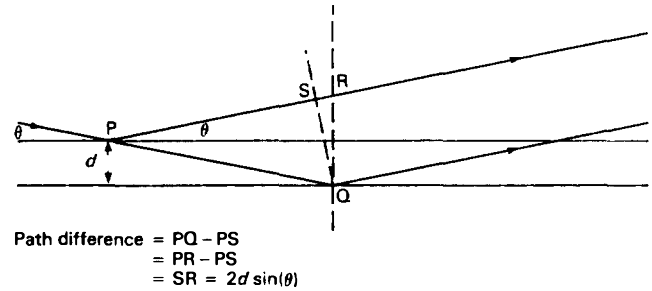

Fig. 4.2 Geometry of X-ray reflection.

such that the angle between them is $2\theta_B$, then it is clear that a strong reflection will only be obtained when the crystal specimen at O is arranged such that the selected plane is in the position shown.

The principle of an X-ray goniometer is then to set up source and detector in fixed positions as above, and provide a means for rotating the crystal specimen about the vertical axis through O in Fig. 4.3 until a strong reflection is obtained. By measuring the angle between the surface of the specimen from which the X-rays are being reflected and the reference line AA', the angle between the surface and the selected atomic plane can be determined. The procedure is in detail dependent on the choice of the atomic plane, and is particularly simple in the case of AT cuts if the (10.1) plane is used because the intersection of this plane and the crystal surface is parallel to the vertical axis of the goniometer. In other cases, several measurements involving different atomic planes may have to be made before the orientation of the plate can be fully determined. These procedures are described in Heising (1946), Bond (1976), and Bottom (1982). Figure 4.4 shows a typical goniometer system incorporating a double reflection arrangement to provide greater precision than the single reflection arrangement outlined above.

In the manufacturing process, X-ray procedures are used both to set up the crystal bars for cutting and subsequently to check the orientation of finished or semi-finished blanks. Cultured quartz bars which are now almost univer-

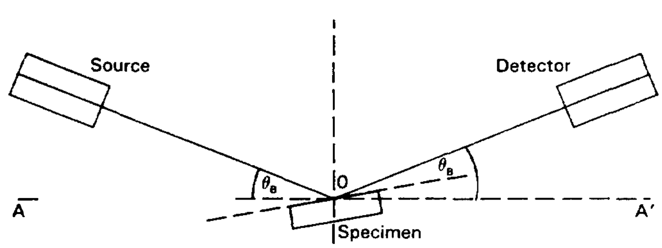

Fig. 4.3 X-ray goniometer arrangement.

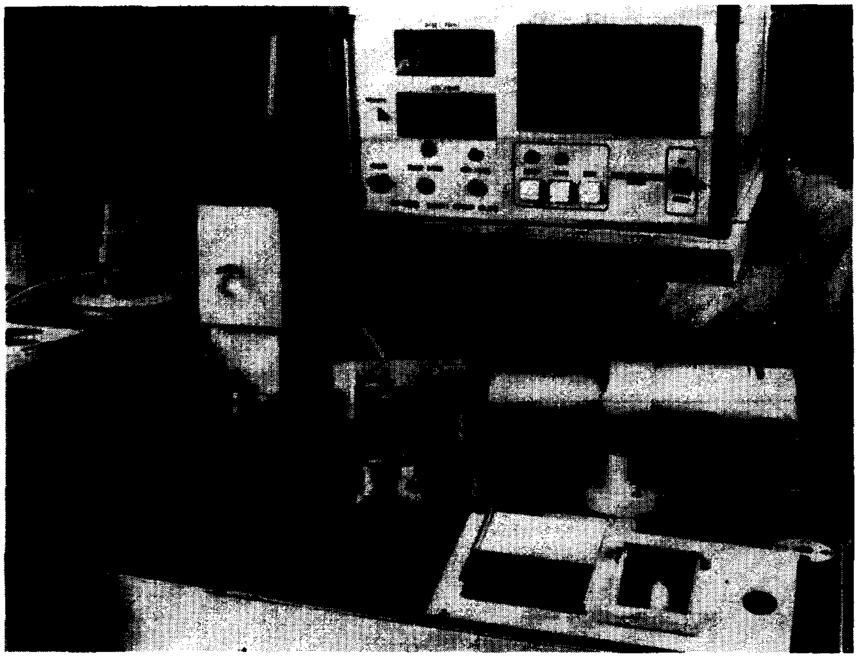

Fig. 4.4 X-ray goniometer.

sally used are supplied by the manufacturers with carefully prepared reference surfaces ground normal to the crystallographic X axis and typically have their length and width along the Y and Z axes, respectively, as in Fig. 4.5. The major surfaces of *lumbered* bars are ground flat and mutually perpendicular, but the ends of the bar show the 'natural' crystal faces, and either one of these natural faces or a lumbered Z surface can be used to set up the bar for cutting. For this purpose the bar is usually mounted on a 'transfer' jig which can be removed bodily from the X-ray machine and loaded directly onto the saw for cutting.

For checking the orientation of finished or semi-finished blanks, vacuum chucks are used to hold the blanks in position against a reference surface on the chuck. The reference may be provided either by a precision ground and lapped surface, or for greater accuracy and repeatability, by a three-point mounting system consisting of ruby tubes carefully set into the chuck surface so as to provide a reference plane perpendicular to the plane of the instrument. A high degree of cleanliness is essential in this operation, since even small dust particles between the blank and the reference surface of the chuck can cause unacceptable errors. For example, a 1 micron particle under one edge of a 5 mm diameter crystal blank will cause an angle error of approximately 0.7 minutes of arc.

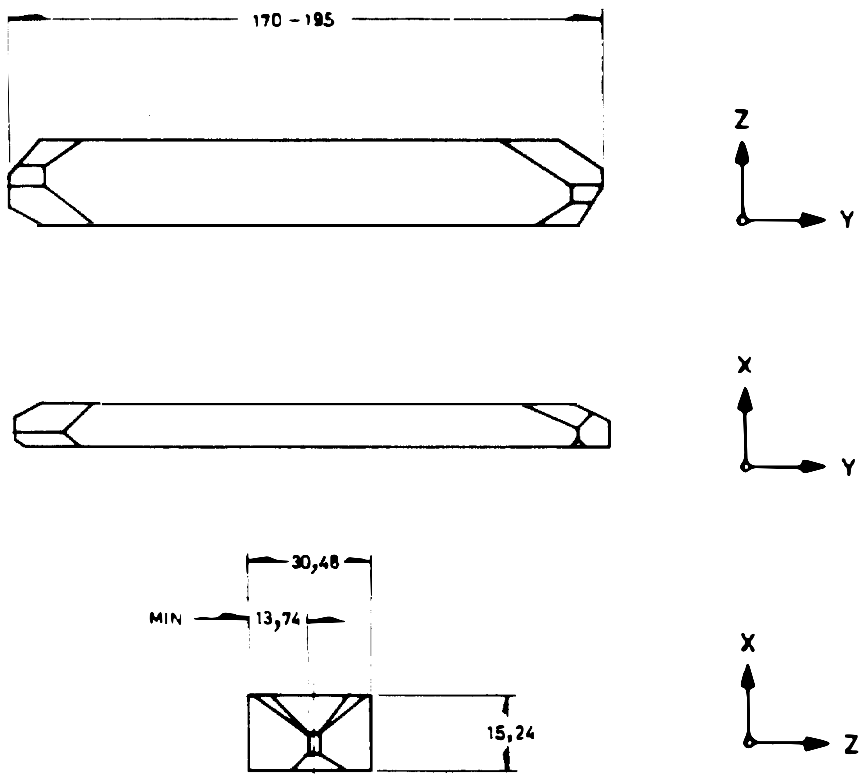

Fig. 4.5 Lumbered quartz bar.

It should also be noted that precision X-ray measurements are wasted unless the surfaces of the blanks to be measured are flat and parallel to a sufficient degree. If tolerances of less than a minute of arc are to be achieved, it is obvious that departures from parallelism of more than a small fraction of a minute cannot be tolerated. Of course, for contoured blanks, the major surfaces are by design not parallel. For plano-convex units, the plano side can still be used for X-ray measurements, and then the critical factor becomes the location of the centre of curvature of the contoured side relative to the plano side. For bi-convex blanks, no reference surface is available for X-ray measurements on the finished unit, and the critical factors are the relative locations of the centres of curvature both to each other and to the original central axis of the initially flat plate. Because of these considerations, it is in practice impossible with biconvex crystals to maintain such close control over orientation as is routine with flat blanks.

4.2 SAWING, DICING AND ROUNDING

Several different methods are in use for sawing quartz bars into wafers. One of the most popular is the 'slurry saw' technique, which is in fact more a lapping process than a sawing one. Figure 4.6 shows a typical saw. One or more quartz bars are rigidly mounted on the bed of the machine, precisely oriented by means of X-ray transfer jigs as previously mentioned. The saw blades consist of tensioned metal strips made up into *blade packs* containing up to a hundred or more blades depending on the desired wafer thickness. The blade pack is then driven in a reciprocating motion along the length of the fixed bed of the machine, back and forth over the quartz bars, with the whole continually being flooded by an oil-based abrasive slurry. The sawing operation takes several hours, but since the machines can be left to run unattended, and are capable of cutting several bars simultaneously, the productivity of the process is high.

The wafers resulting from the sawing process are rectangular in shape, and each contains in its central region a portion of the original seed crystal used in the growth of the bar, which cannot be used owing to the high density of defects and impurities found in the immediate neighbourhood of the seed. Thus the central region of the wafers has to be removed. The wafers are

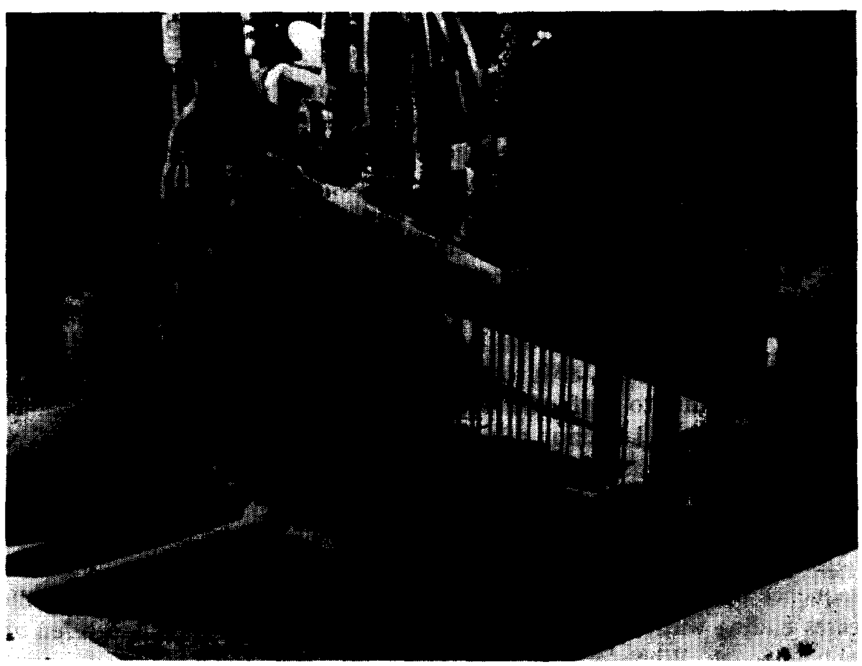

Fig. 4.6 Slurry saw.

therefore first lapped to remove any wedging that may have resulted from the sawing operation, and then waxed or cemented into long stacks. The stacks are then sawn into two stacks of roughly square *dice*, the central region being discarded. Depending on the type of resonator required, the next operation is then either to surface grind the dice, still in their stacks, to specified edge dimensions, or else to *circularize* or *round* them to a specified diameter. The rounding operation may be carried out on conventional cylindrical grinders or on centreless grinders, the latter generally requiring less fixturing and giving a better edge finish. However, the centreless grinder can only produce a completely circular stack, and it is often desirable to retain a small flat perpendicular to the X axis on the blanks to aid orientation at subsequent stages. With appropriate fixtures this is straightforward to achieve on a conventional grinder, by offsetting the axis of the stack relative to the axis of the machine, but requires an additional operation when using a centreless grinder.

After the edging or rounding operations, the dice or blanks are separated and cleaned ready for subsequent operations. At this stage, the surface finish is relatively coarse, and the blanks are relatively thick, it being impractical to cut wafers much thinner than two to three hundred microns.

4.3 LAPPING AND POLISHING

For low frequency resonators such as extensional, flexural and face shear types, the blank frequency is essentially determined by the lateral dimensions of the blank, with the thickness governing the motional inductance. For thickness mode resonators, the reverse is true, the thickness being the main determinant of the blank frequency. For the AT-cut, in the fundamental frequency range 1 to 50 MHz, the thickness ranges from about 2 mm down to 33 microns, with the tolerances required being of the order of 0.1%. There are accompanying severe requirements on blank flatness and parallelism. The surface finish required can be assessed in terms of the acoustic wavelength in the resonator, as it seems physically reasonable to assume that to avoid losses due to surface irregularities, such surface damage must be restricted to a small fraction of a wavelength. This immediately leads to the conclusion that the degree of surface finish required increases with frequency, and in particular that overtone resonators require a higher degree of finish than a fundamental mode resonator of the same thickness.

In order to achieve the required thickness and surface finish, a graded sequence of double-sided lapping operations is commonly used, in some cases ending with a polishing operation in which the blanks are given an optical polish. When large amounts of material have to be removed, one of the double-sided lapping stages may be replaced by single-sided lapping,

Fig. 4.7 Planetary lap.

which has the advantage of better control over the orientation angle but the disadvantage of not maintaining parallelism. Hence double-sided lapping is always used after any single-sided operation.

Double-sided lapping machines are of two main types, *planetary* and *eccentric* or *pin* laps. In both types, the blanks are carried around between cast iron lapping plates in an oil or water based abrasive slurry. In the planetary system (Fig. 4.7) the lapping carriers have the form shown in Fig. 4.8, and are located between toothed inner and outer gears. The gear

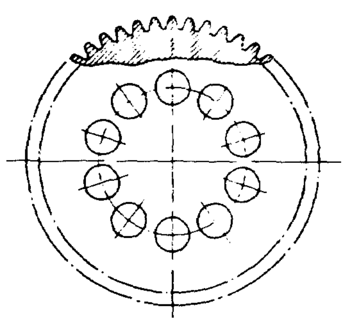

Fig. 4.8 Planetary lap carrier.

ratios are so chosen that in the motion of the blanks, the surfaces of the plates wear uniformly. This helps to maintain both the flatness of the plates themselves, and also ensures a corresponding flatness in the blanks, but nevertheless the lapping plates have frequently to be removed and lapped flat on a larger machine to guarantee blank quality. Blank parallelism is ensured by regular *transposition* of the blanks in the lapload. Transposition is a systematic interchange of blanks from opposite sides of the lapload designed to prevent a situation from arising where all the thicker blanks are grouped together on one side of the load. If such a situation does occur, in which the upper lap plate is resting on the blanks at some small angle to the lower plate, then there is no intrinsic correcting mechanism and without transposition to redistribute the thicker blanks, the result would be both an increasing spread in frequency between the blanks in the load and a pronounced 'wedging' of the blanks.

In the pin or eccentric lap (Fig. 4.9) the lapping principles are the same, but

Fig. 4.9 Pin lap.

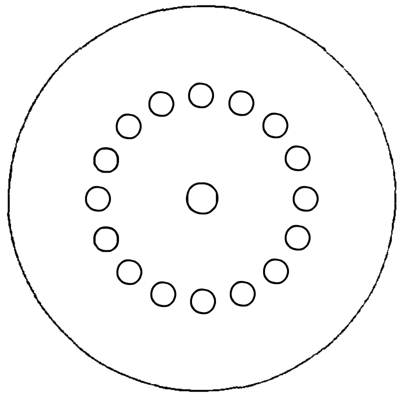

Fig. 4.10 Pin lap carrier.

the mechanism by which the blanks are driven around between the lapping plates differs. The blanks are held in a carrier (Fig. 4.10) consisting of a sheet of 'mylar' film or similar material, supported in its centre, and free to rotate about a pin that is itself located slightly off centre relative to the vertical axis of the machine (Fig. 4.11) In operation, this eccentricity of the carrier centre once again results in a motion in which each individual blank eventually traverses all points on the surfaces of the lapping plates, with the object being to preserve the flatness of both lap plates and blanks. This ideal is not of course achieved in practice, so that as in the planetary case, the lap plates have frequently to be removed for reconditioning.

In both types of lap it is common to use some means of automatic control to terminate the operation when the desired thickness or frequency has been reached. The traditional technique is simply to detect the transient

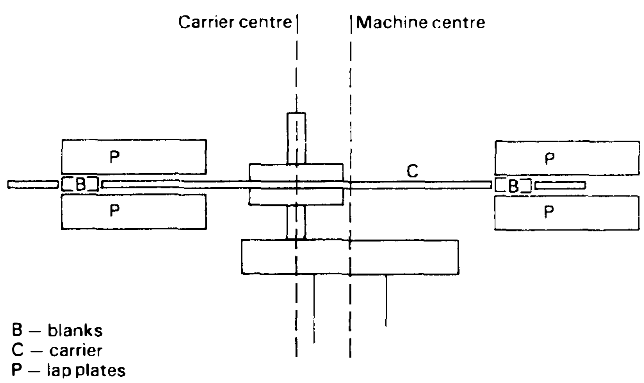

Fig. 4.11 Cross-section of pin lap geometry.

oscillations of the blanks excited by the lapping process using a sensitive radio receiver connected to one of the plates as an aerial. These oscillations appear as a noise signal centred on the blank frequency, and can either be used to monitor the progress of the operation or to provide an automatic shut-off by setting the receiver to a target frequency. A more sophisticated technique is to insert electrodes into both upper and lower lapping plates and to monitor the change in impedance that occurs when a blank passes between the electrodes. A swept frequency RF signal is applied to the electrodes and during each sweep the frequencies at which impedance changes occur are stored. At the end of the sweep, the mean or maximum frequency stored, together with the spread in the stored frequencies, can be displayed, and the machine shut off when a preset target frequency is reached.

The abrasives used in the lapping operations are generally carefully graded aluminium oxide powders, with silicon carbide often being used for the coarser stages, and sub-micron cerium oxide powders being used for polishing. The coarser the abrasive, the more rapid the stock removal but the poorer the surface finish, so it is usual to grade the lapping operations. In the initial stages a coarse abrasive is used, and in subsequent stages, successively finer materials. In each stage, the amount of material removed is related by rule of thumb to the size of the previous abrasive, so that at the end of each stage the surface finish of the blanks is characteristic of the abrasive used in that stage rather than a previous one. Polishing operations differ little in principle from lapping operations. The abrasive used is much finer, and in addition the lapping plates are usually covered with a pad of some material. The particular material used varies from manufacturer to manufacturer, but as a general rule, soft pads quickly produce a high polish with relatively coarse abrasives but do not maintain flatness and parallelism, whereas harder pads have the reverse characteristics.

4.4 CONTOURING AND BEVELLING

Low frequency thickness mode resonators such as the AT are frequently given a complete or partial spherical contour on one or both major surfaces, in order to restrict the vibrating area of the blank to its central region and thus avoid mounting losses and coupling to unwanted modes at the edges of the blank. Contouring methods fall into two distinct classes, one suited to relatively high volume production, the other to small batch production.

The first group comprises those techniques commonly referred to as *tube* or *drum* contouring, in which the mechanism involved is very similar to that responsible for the rounding of pebbles in a river bed. The procedure is to load a quantity of blanks, previously lapped to the desired final thickness, together with a quantity of abrasive powder, into a pipe or drum of internal

Fig. 4.12 Contouring machine.

radius equal to the desired radius of curvature for the blanks. The tube and its contents are then continuously rotated about the tube's longitudinal axis in such a way that the blanks are subject to a gentle tumbling action, which over a period of perhaps several days results in the blanks taking on the contour of the tube. Naturally both surfaces are symmetrically affected, so that the contour is a biconvex one, and depending upon the time allowed in the tube, will either be complete or a partial contour (or bevel). The process is essentially statistical in nature, that is not all blanks will attain the same degree of contour in the same period of time, so that periodic monitoring is essential.

Although planoconvex contours can be produced in tube contouring by the expedient of cementing blanks together in pairs, such contours are usually produced by methods derived from the optical industry, which comprise the second of the two classes mentioned above. Figure 4.12 shows a typical contouring machine using a 'dioptre cup'. This is a cast iron tool with a concave spherical surface machined on its upper face, and designed to be mounted on a vertical spindle whose axis goes through the centre of curvature of the concave surface. In operation the tool is rotated about this vertical axis and the crystal blank, usually mounted on a brass 'contouring button', is swept backwards and forwards across the cup, from a point near its edge to a point just past its centre, with the whole being flooded by an abrasive slurry.

The blank can either be held manually or, as in the illustration, held by a mechanical arm locating in a recess machined in the back of the button. In the manual case, the blank must be continually rotated about its own axis to maintain the spherical character of the contour; in the mechanical case, the rotation required is generated by the rotation of the cup, provided only that the button is free to spin about the axis of the mechanical arm. Clearly this process is intrinsically better suited to small batch production rather than high volume work, but nevertheless is extensively used in all classes of production. Consequently the cost savings that result from volume production in the higher frequency ranges cannot necessarily be achieved at low frequencies.