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Anderson et al.

[11] **3,736,426**

[45] **May 29, 1973**

[54] METHODS OF AND APPARATUS FOR INSPECTING CRYSTALS

[75] Inventors: **Albin R. Anderson**, Lowell; **Robert P. Grenier**, Newburyport, both of Mass.; **Peter R. Perri**, Atkinson, N.H.

[73] Assignee: **Western Electric Company, Incorporated**, New York, N.Y.

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[52] **U.S. Cl.** **250/51.5**, 209/111.5

[51] **Int. Cl.** **G01n 23/20**, H01j 37/20

[58] **Field of Search** 250/51.5; 209/111.5

[56] **References Cited**

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Primary Examiner—James W. Lawrence
Assistant Examiner—B. C. Anderson
Attorney—W. M. Kain and J. B. Hoofnagle, Jr.

[57] **ABSTRACT**

In order to determine the angular orientation of atomic planes in a crystal relative to a reference surface thereof, the crystal is inspected by an X-ray defraction technique in which a pair of X-ray beams are sequentially passed through the crystal from opposite directions while the crystal is rotated through a small arc and monitored for Bragg angle reflections. The two angles at which reflections occur are then averaged to determine an average Bragg angle of reflection. This technique compensates for the situation in which the atomic planes of the crystal are completely oblique to the reference surface by cancelling component vectors of reflection introduced by the complete obliqueness.

7 Claims, 6 Drawing Figures

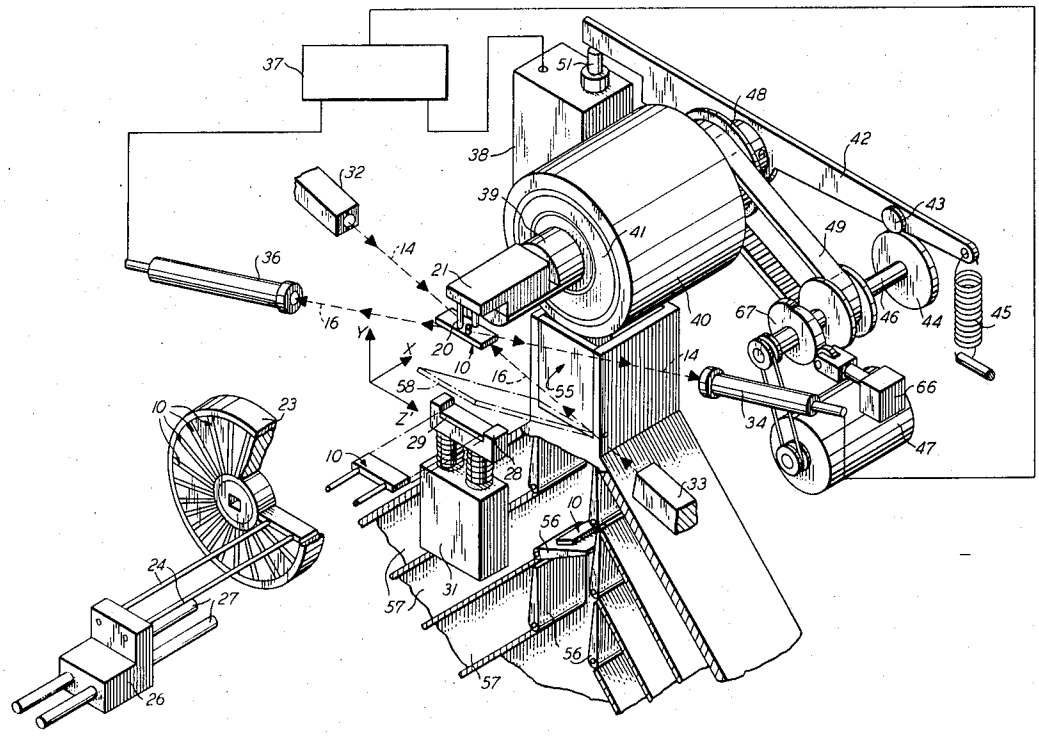
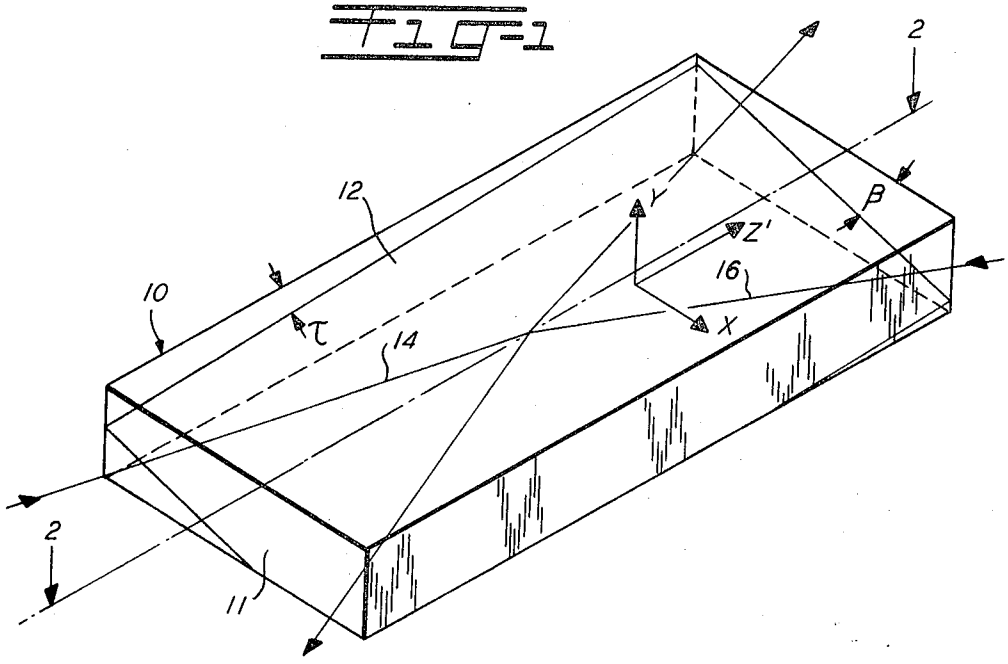


FIG-1



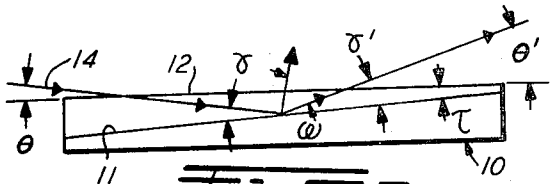


FIG-2

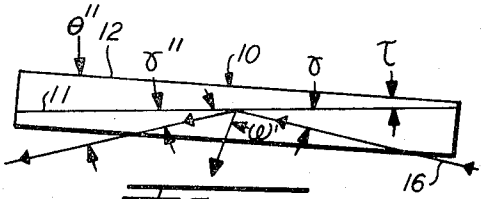


FIG-3

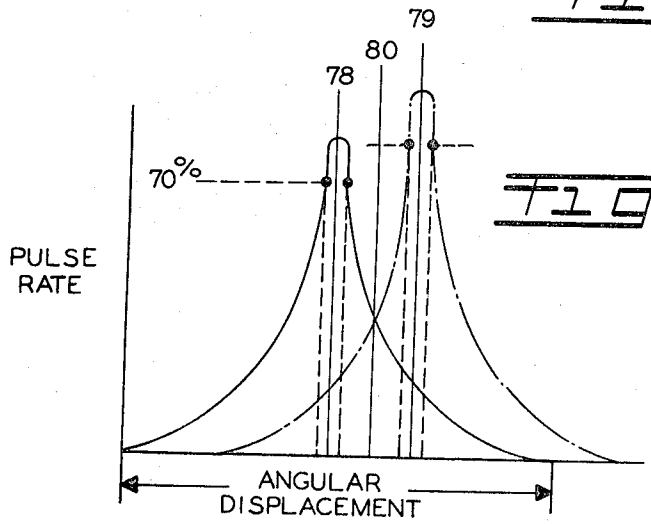


FIG-6

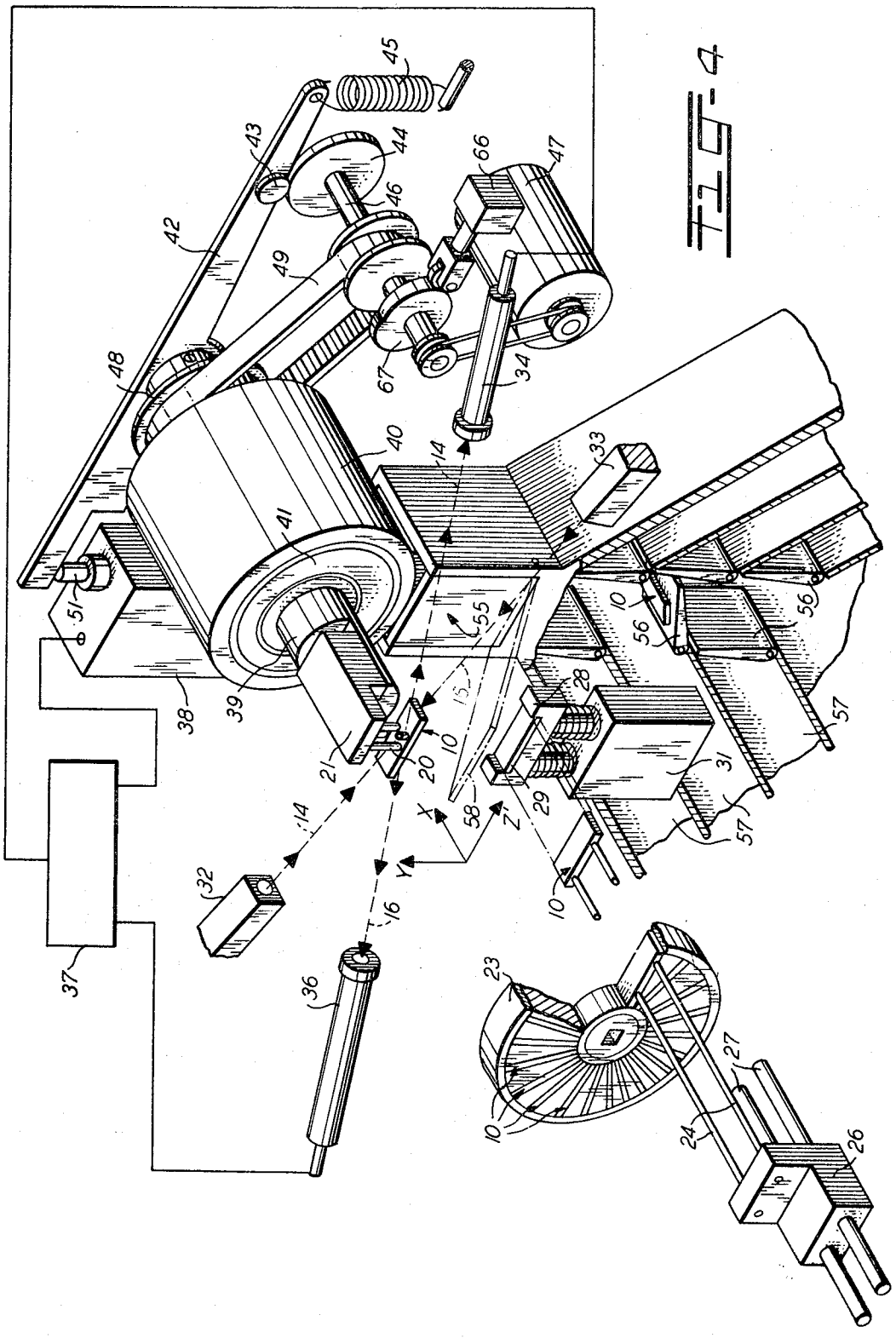

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FIG-4

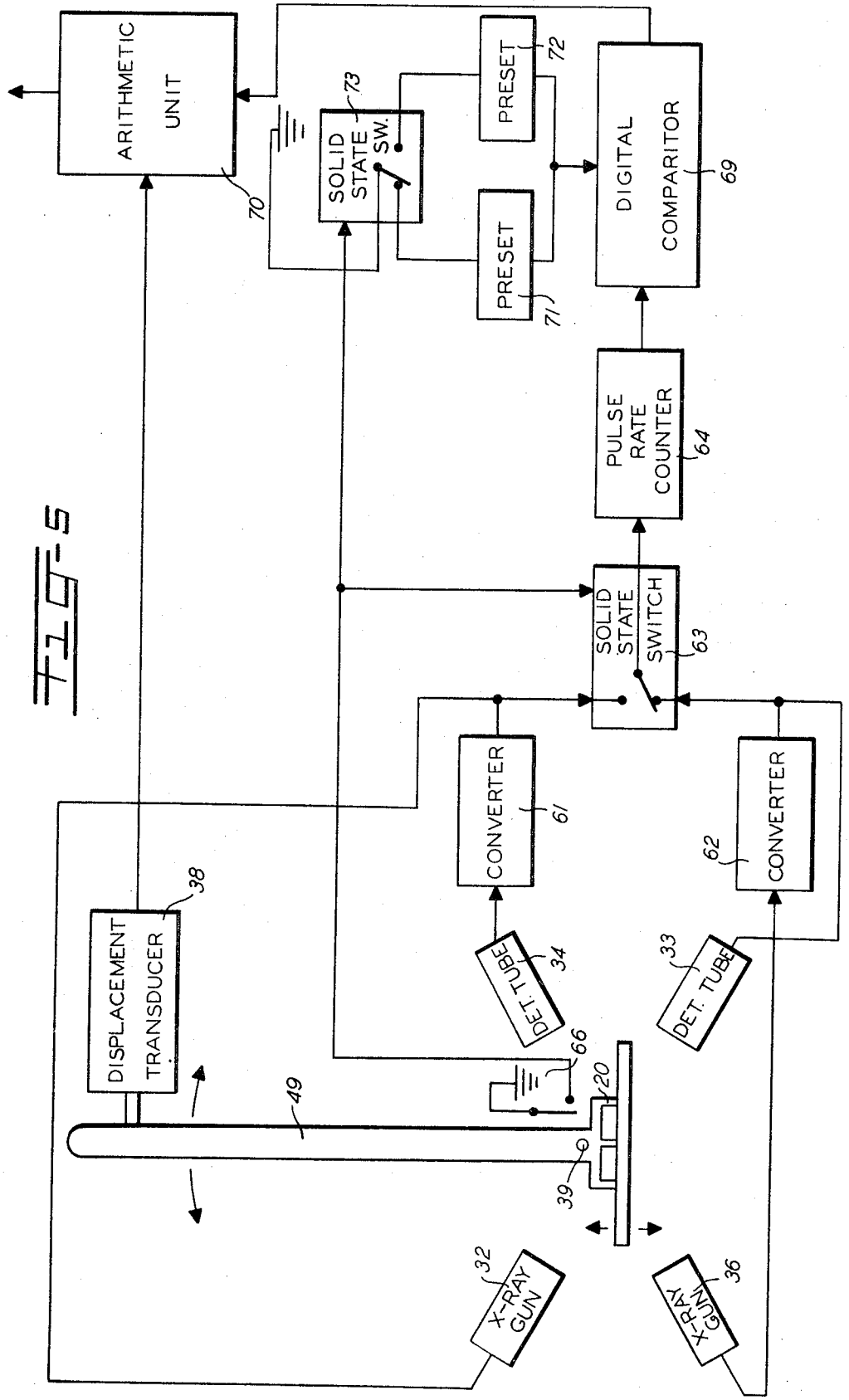

ARITHMETIC UNIT
70
SOLID STATE SW.
73
PRESET
72
PRESET
71
DIGITAL COMPARITOR
69
PULSE RATE COUNTER
64
SOLID STATE SWITCH
63
CONVERTER
61
CONVERTER
62
DISPLACEMENT TRANSDUCER
38
DET. TUBE
34
DET. TUBE
33
66
49
20
39
X-RAY GUN
32
X-RAY GUN
36

FIG-5

METHODS OF AND APPARATUS FOR INSPECTING CRYSTALS

FIELD OF THE INVENTION

The present invention relates generally to the manufacture of piezoelectric quartz crystal elements, and more particularly to automatic apparatus adapted to measure the axial orientation of crystal blanks and to sort the blanks according to the orientation measurements.

BACKGROUND OF THE INVENTION

Using piezoelectric quartz crystals in electronic systems is well known. A piezoelectric crystal undergoes a change in dimension or form proportional to an applied electrical potential. Conversely, the crystal generates a surface charge when subjected to stress. The crystal is said to be a piezoelectric resonator when the mechanical resonances of the crystal itself are used to control frequency response.

Crystal blanks for piezoelectric units are cut from quartz stones. When the crystal blank is excited, the resulting modes of motion and the properties of those modes depend markedly on how the surfaces of the cut crystal blanks are oriented relative to the bases of the uncut stones. The angle at which a crystal blank is cut with reference to the natural crystal axis of the uncut stone determines the temperature coefficient of the frequency of the crystal unit. Obviously, to preclude or minimize departures from an assigned frequency as a result of temperature variations, it is essential that this coefficient be as close as possible to zero.

A rectangular uncut quartz stone has a Z or optic axis extending in a longitudinal direction, an X axis extending through one of the apexes of the stone and a Y axis extending normal to both the Z and X axes. The stone is cut along what is generally referred to as the Z'-X plane and the angle defined by the Z axis and the resulting crystal face or the Z—Z' angle is especially significant as regards to the temperature coefficient. For AT cuts, the crystal blank is rotated about the X axis and cut along a plane that makes an angle with the Z axis of approximately 35.12°. There are of course many other useful crystal cuts involving different angles. This angle can be cut for any particular nominal frequency so that the unit will be stable throughout an extended temperature range, running for example from −55° to +90° C.

The Z—Z' crystal angle is highly critical. It is the current practice to cut the Z—Z' angle with diamond saws but the state of this art is not such that it is presently possible to control the angle with sufficient precision so as to produce all blanks within the desired angular specification. On the other hand, the Z—Z' angle can be chosen for any nominal frequency so that the temperature coefficient of frequency is close to zero. Consequently, given broad production requirements for blanks covering the entire frequency spectrum, no blank need be rejected. But since the blanks so cut are different, they must first be individually measured by X-ray diffraction techniques and then sorted into angular increments preparatory to final processing. Blanks from the proper incremental class will thereafter be selected for the fabrication of a group of crystals having a predetermined frequency.

In existing X-ray diffraction techniques for determining the angle between the face of a crystal and its atomic plane, an X-ray beam is directed at the face of the crystal while the crystal is rotated on a goniometer turntable. At solely one specific angle between the atomic plane of the crystal and the X-ray beam there will be X-ray reflection. This angle is known as the Bragg angle. A detector is positioned to intercept the reflected beam as the face of the crystal lies against a reference surface. The angular position of the crystal can then be determined electronically when the detector receives a reflection, thereby establishing the Bragg angle.

PRIOR ART AND TECHNICAL CONSIDERATIONS

In one prior art procedure, the X-ray measurement is carried out manually by peaking a signal output meter for maximum reflection and then reading a vernier position indicator mechanically coupled to the turntable to fix the crystal angle. This procedure is of course time-consuming and requires that the turntable be swung slowly in either direction until the peak position is found and the turntable movement arrested to enable a vernier reading to be taken. Thereupon the blank is removed from the turntable and placed into an appropriate grouping. Because of the skill entailed in making the X-ray measurements and the manual operations called upon both in determining the peak position of the cyrstal blanks and in sorting the blanks, this method does not lend itself to large scale mechanized production. In addition, the manual technique does not ensure the degree of accuracy necessary in current transmission equipment.

In order to increase accuracy and production, automated X-ray equipment has been introduced in which there is provided means for automatically feeding crystal wafer blanks, one at a time, with the X-axis oriented to a Z-axis determining position. At the Z-axis determining position, the crystal wafer blanks are held by a vacuum after being secured in a reference position to a rotating spindle of the X-ray machine which is automatically rotated through a predetermined angle. During this rotation, a shaft encoder provides an output signal indicating the degree of rotation of the spindle in digital form while X-rays are impinged on the crystal. When Bragg angle reflections from the crystal planes occur, the reflections are detected by a radiation detector, the electrical output of which is amplified and fed to a peak sensing circuit. At the peak of the sensed reflected X-rays, the peak sensing circuit produces a pulse which is digitally encoded by the shaft encoder, thus indicating digitally the angle of rotation at which the maximum peak occurs. This digital signal from the shaft encoder is used to operate logic circuitry which, in turn, controls a tree type sorter to sort the wafer blanks into one of a large number of bins in accordance with the determined angle of the Z-axis.

These prior art procedures while usually determining the angular orientation of most crystal planes with adequate accuracy, do not however take into account and compensate for crystal planes which might be skewed in relation to the reference surface of the crystal. In otherwords, crystals in which the crystal planes make angles with both the Z' and X axes of the reference surface of the crystal. Accordingly, a method of and apparatus for discovering and compensating for skewed crystal planes is needed.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide new and improved methods of and apparatus for more accurately determining the angle that the crystal planes of a crystal make with a reference surface of the crystal.

An additional object of this invention is to provide methods of and apparatus for compensating for component vectors introduced into measurements of crystal plane angles due to skewed orientations of the crystal planes relative to a reference surface.

With these and other objects in view, the present invention contemplates supporting a crystal to be measured on a goniometer spindle for oscillation about the X-axis of the crystal while sequentially directing a first X-ray beam through a reference surface of the crystal while the crystal oscillates in a small arc and then directing a second X-ray beam through a surface opposite the reference surface while the spindle again oscillates in a small arc. First and second X-ray detectors are positioned adjacent the reference surface and opposite surface, respectively, to detect the angles of rotation at which Bragg angle reflections occur. These angles are then averaged by electronic circuitry to obtain the correct angle that the crystal planes of the crystal make with the reference surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an enlarged isometric view of a quartz crystal of the type inspected by the instant invention schematically showing one atomic plane of many within the crystal skewed relative to a reference surface of the crystal and showing X-ray beams impinging upon and being reflected from top and bottom sides of the atomic plane;

FIG. 2 is a view taken along line 2—2 of FIG. 1 showing the angles that a reflected X-ray beam makes with the top surface of the atomic plane and with the reference surface of the crystal;

FIG. 3 is a view similar to FIG. 2, however, the quartz crystal has been rotated slightly in the clockwise direction and an X-ray beam is shown reflecting from the bottom surface of the atomic plane;

FIG. 4 is an isometric view, schematically arranged, of an X-ray machine and sorting device which may be used to practice the instant invention;

FIG. 5 is a block diagram of a circuit which may be used to control the X-ray machine and sorting device of FIG. 2; and

FIG. 6 is a graph plotting the intensity of two X-ray reflections from a crystal as function of the angle of incidence of X-ray beams with the crystal.

DETAILED DESCRIPTION

Referring now to FIGS. 1–3, a rectangular quartz crystal, designated generally by the numeral **10**, is shown with a single atomic plane **11** disposed therein which, for purposes of illustration, is indicative of all the atomic planes in the crystal each of which is parallel to the illustrated plane **11**. In FIG. 1, the atomic plane **11** is shown skewed in relation to a top reference surface **12** of the crystal **10** forming angles τ in the Z'-Y plane and β in the X-Y plane. For purposes of illustration, the extent of obliqueness of the plane **11** relative to the reference surface **12** is exaggerated. Ordinarily, the angle between the atomic plane **11** and reference surface **12** is approximately 3°. It should be noted that FIG. 1 depicts a situation where the plane **11** is completely oblique in relation to the surface **12**. In other words, the plane **11** makes angles with both the Z' and X axes of the surface **12**. The purpose of the instant invention is to accurately determine the angle τ.

In FIG. 2 an X-ray beam **14** contained in the Z'-Y plane is shown passing through the reference surface **12** and forming an angle γ with the atomic plane **11**. Assuming γ is the Bragg angle, a reflection will occur from the atomic plane **11** at an angle γ'. γ' differs from γ because upon being reflected, the beam **14** moves out of the Z'-Y plane due to an angular component ω introduced into the reflection because of an angle β that the atomic plane **11** makes with the reference surface **12** in the Z'-Y plane. The component ω may make the angle γ' slightly greater as is the case illustrated or slightly less as would be the case if the angle β opened in the opposite direction.

The X-ray beam **14** also makes an incidence angle θ and reflection angle θ' with the reference surface **12**. The reflection angle θ' differs from the angle of incidence θ for two reasons. First of all θ' is larger than θ due to the angle τ that the atomic plane **11** makes with the reference surface **12** or the Z' axis of the crystal **10**. Secondly, θ' is affected by the angular component in the same way as γ' is affected in that the angle of the atomic plane **12** causes the X-ray beam **14** to bend out of its incidence plane thereby slightly increasing the size of θ' over what it would be if β were zero.

Determining the angle θ' enables one to determine the angle τ because the Bragg angle for the quartz crystals is known to be 13° 20'. By simply substracting 13° 20' from the angle θ' the angle τ is obtained. Generally the angle θ' will be approximately 16° 20' in which case τ will be 3° 00'. However, it can be readily seen that any error in θ' will result in an error in computing the angle τ. If the angle β is not zero then there will be an error in the angle θ' because of the angular component ω. The prior art methods of and apparatus for determining the angle θ' do not compensate for the component ω. Consequently, whenever an angle exists, the prior art techniques result in an inaccurate determination of the angle τ.

The present invention compensates for the component ω by passing an additional oppositely directed X-ray beam **16** through a surface **17** which is opposite the reference surface **12**. As seen in FIG. 3, the beam **16** reflects from the bottom of the atomic plane **11** upon impinging on the atomic plane at an angle equal to the Bragg angle of reflection γ. Due to the angle β, the beam **16** will form an angle γ'' upon being reflected from the bottom of plane **11**. γ'' is different from γ for the same reason that the angle γ' formed by beam **14** is different from γ upon being reflected from the top of plane **11**. The reason of course being that an angular component ω' is introduced into the angle of reflection γ''. However, ω' is opposite in sign to ω and will decrease the size of γ'' by the same amount that ω increases the size of γ'. Accordingly, an angle θ'' between the reflected beam **16** and the reference surface **12** will be decreased by an equivalent amount. Now if θ'' is measured and then averaged with θ', then ω' and ω will cancel one another out giving an accurate determination of τ once the Bragg angle γ which is a known value is subtracted from the average of θ'' and θ'.

Referring now to FIG. 4 where there is shown an X-ray machine and sorter for practicing the principles of the invention, the quartz crystal **10** is supported by three nozzles **20** of a vacuum chuck **21** for rotary movement about the X-axis of the crystal. The crystal **10** is initially stored with a plurality of other crystals within a rotary magazine **23.** As the magazine **23** indexes in the counterclockwise direction, a carriage **26** which reciprocates on a pair of guide rods **27** engages one of the crystals **10** with a pair of push rods **24** and advances the crystal onto an aligning platform **28** which is spring-supported. The aligning platform **28** has a slot **29** in the top thereof which closely approximates the configuration of the crystals **10** to ensure that each crystal is identically aligned with the nozzles **20.** After receiving one of the crystals **10,** the aligning platform **28** is advanced upwardly by a vertical transport **31,** which spring supports the aligning platform, to engage the crystal with the vacuum nozzles **20.** The vertical transport then lowers away from the crystal **10** leaving the crystal supported by the nozzles **20** and ready for sequential inspection by the X-ray beams **14** and **16** as described in FIG. **1.**

The X-ray beam **14** is generated by a first X-ray gun **32** positioned above and to the left of the crystal **10** to direct beam **14** at an angle of approximately 10° 19′ to the Z′ axis of the crystal while the X-ray beam **16** is generated by a gun **33** positioned below and to the right of the crystal to direct beam **16** at an identical angle. Associated with the pair of guns **32** and **33** are a pair of Geiger Mueller X-ray detector tubes **34** and **36,** respectively, which sequentially feed signals into a test set designated generally by the numeral **37** when an X-ray reflection is detected by either tube. Circuitry (not shown) is provided to energize the X-ray gun **32** while the crystal oscillates through an arc of about **10** minutes. The gun **32** is then de-energized and the gun **33** energized while the crystal **10** again oscillates through an arc of about 10 minutes.

The test set **37** also receives signals from a displacement transducer **38** indicative of the angular position of the crystal **10** at which X-ray reflections are occurring. The angular orientation of the crystal **10** is achieved by oscillating a spindle **39** of a goniometer **40** to vary the angular position of the vacuum chuck **21** which is secured to one end of the spindle.

The spindle **39** is mounted within a bearing raceway **41** and is oscillated by an arm **42** which is rigidly secured to the spindle. The arm **42** has a follower **43** at one end thereof which is held in engagement with a cam **44** by a spring **45.** The cam **44** is mounted on a shaft **46** which is rotated in one direction by a motor **47.** In the preferred embodiment, the cam **44** has a double-lobed profile so that the follower **43** rises and falls twice for each revolution of the shaft **46.** While the follower **43** is being lifted by an advancing high profile of the cam **44,** the arm **42** pivots in a counterclockwise direction rotating the spindle **39** in a counterclockwise direction within the raceway **41.** While the follower **43** is lowering on a low profile portion of the cam **44,** the arm **42** pivots in the clockwise direction rotating the spindle **39** in a clockwise direction within the raceway **41.** While the spindle **39** is thus oscillating, the raceway **41** is being constantly rotated in one direction by a sprocket **48** which is driven by the shaft **46** with a belt **49.** This insures that the various parts of the raceway **41** wear evenly as the spindle **39** oscillates to change the angular orientation of the crystal **10.**

The left end of the arm **42** engages a plunger **51** located within the transducer **38** and reciprocates the plunger against an upward bias of a spring (not shown). The position of the plunger **51** is calibrated to be indicative of the angular displacement of the spindle **39** and is thereby indicative of the angular displacement of the crystal **10.** As described hereinafter, the signals from tubes **36** are coordinated with the signals from transducer **38** and averaged to accurately disclose the orientation of atomic planes **11** with respect to the reference surface **12** of the crystal **10** by observing Bragg angle reflections.

After each crystal **10** is scanned by the X-ray beams **14** and **16** and analized by the test set **37,** it is directed into a tree sorter, designated generally by the numeral **55.** The tree sorter **55** has a plurality of sorting gates **56** each of which is connected to a separate bin (not shown) by chutes **57.** Each sorting gate **56** is assigned a value corresponding to an angular orientation of atomic planes **11** in the crystal **10.** When the test set **37** determines that angular orientation, only the sorting gate **56** corresponding thereto will be opened.

Since the transport **31** is positioned beneath the nozzles **20,** the tree sorter **55** must be set back from the nozzles. Consequently, a directing gate **58** must be hinged to the tree sorter **55** to swing beneath the nozzles **20** and the crystal **10** prior to releasing the crystal in order to channel the crystal into the sorter.

The elements of the test set **37** are more fully disclosed in the block diagram of FIG. **5** where the crystal **10** is shown being monitored by the detector tubes **34** and **36.** Connected to the detectors **34** and **36** are converters **61** and **62,** respectively, which convert pulses from the tubes **34** and **36** into signal pulses suitable for pulse rate counting. The converters **61** and **62** are both connected to a solid state switch **63** which determines whether the X-ray gun **32** is generating the beam **14** and a signal from detector **34** is being applied to a pulse rate counter **64** or whether the X-ray gun **33** is generating the beam **16** and a signal from the detector **36** is being applied to the pulse rate counter.

The setting of the solid state switch **63** is determined by a cam operated mechanical switch **66** which is closed during only half a revolution of the shaft **46** by a single lobed cam **67** (FIG. **4**) mounted on the shaft **46** (FIG. **4**). When the switch **66** is closed, the switch **63** transmits pulses from the converter **61** to the pulse rate counter **64** and when the switch **66** is open, the switch **63** transmits pulses from the converter **62** to the pulse rate counter. Since the cam **67** (FIG. **4**) is single lobed and the cam **44** (FIG. **4**) double lobed, the arm **42** will undergo two oscillations for each condition of the switch **63.** The crystal **10** which is oscillated by the arm **42** via the spindle **39** is therefore rotated both clockwise and counterclockwise each time it is scanned by one of the X-ray beams **14** or **16.**

The pulse rate counter **64** applies a digital signal indicative of pulses per millisecond to a programmable digital comparitor **69** which is programmed to relay signals from the pulse rate counter to an arithmetic unit **70** when instructed to do so by presets **71** and **72.** The presets **71** and **72** are operated selectively by a solid state switch **73** which is controlled by the cam operated mechanical switch **66.** When the switch **66** is closed, signals from converter **61** and preset **71** are applied si-

multaneously to the comparitor **69**. When the switch **66** is open, signals from the converter **62** and preset **72** are applied to the comparitor **69**.

Referring now to FIG. **6** where pulse rates generated by the X-ray beams **14** and **16** are plotted against angular displacement to form curves **74** and **76**, it is seen that the pulse rates rapidly increase as the crystal **10** approaches a critical angle at which reflectivity is a maximum and then rapidly decline. The presets **71** and **72** are set at a pulse rate intensity of about seventy per cent of the maximum pulse rate intensity expected to occur at the critical angle. Since signals from the detectors **34** and **36** are different due to their different orientations relative to the crystal **10**, the presets **71** and **72** will of course be set at different values which is why two presets are used. If the pulse rate intensity of either signal does not reach the preset value, then an output signal from the digital comparitor **69** instructs the X-ray machine of FIG. **2** to reject the crystal **10** under consideration, whereupon the vacuum chuck **21** (FIG. **4**) releases the crystal and it is directed by the sorting tree **55** (FIG. **4**) into a reject bin (not shown).

Referring now to FIG. **5**, if the intensity of the signal from the pulse rate counter **64** exceeds the preset value being impressed on the digital comparitor **69** by either preset **71** or **72**, then the comparitor instructs the arithmetic unit **70** to accept angular displacement readings from the displacement transducer **38** for as long as the pulse rate counter continues to exceed the preset value. The arithmetic unit **70** then computes mean values represented by vertical lines **78** and **79** (FIG. **4**) of the angular displacement readings. If the mean value of the angular displacement is determined while detector **34** is generating pulses as represented by the line **78**, then the mean value is temporarily stored. However, if the mean value of the angular displacement is determined while detector **36** is generating pulses as represented by line **79**, then the mean value is averaged with the stored mean value **78** to compute a final mean value, represented by the line **80**. The final mean value **80** is a very accurate determination of the angular displacement at which Bragg reflections occur in individual crystals **10**. As mentioned earlier in the discussion of FIG. **1**, when the angles of reflection of the X-ray beams **14** and **16** are averaged, the angular components ω and ω' caused by oblique or skewed orientation of the atomic planes **11** cancel one another out.

A signal indicative of the true angle of reflection is then transmitted by the arithmetic unit **70** to the X-ray machine of FIG. **4** to open the proper gate **56** in the tree sorter **55**. After the proper sorting gate **56** is opened, the directing gate **58** is opened and the vacuum released on the nozzles **20** to drop the crystal **10** onto the directing gate whereupon the crystal is directed into the chute and thereafter into the proper bin. In this manner, crystals **10** having identical or approximately identical axial orientations of their respective atomic planes **11** relative to their reference surfaces **12** in the Z' direction, are separated from an assortment of crystals having various axial orientations.

What is claimed is:

1. In a method of measuring the axial orientation of atomic planes in a crystal relative to a reference surface of the crystal where the atomic planes may be completely oblique relative to the reference surface, comprising the steps of:

rotating the crystal about an axis thereof through an arc,

passing radiant energy through a reference surface of the crystal while the crystal is being rotated,

determining the angle of rotation at which radiant energy is reflected through the reference surface of the crystal from the atomic planes,

storing the determined angle,

passing radiant energy through a surface of the crystal opposite the reference surface,

determining the angle of rotation at which radiant energy is reflected through the opposite surface from the atomic planes, and

averaging the angle at which radiant energy is reflected through the opposite surface with the stored angle to compensate for inaccuracies introduced into the measurements because of the complete obliqueness.

2. The method of claim **1** wherein the radiation employed is X-radiation.

3. In a method of determining the axial orientation of atomic planes in a crystal wherein the crystal is rotated through a sector intersected by an X-ray beam which is, in turn, monitored for reflections through one surface of the crystal from the atomic planes to determine the angle at which reflections occur, the improvement comprising the steps of:

again rotating the crystal,

impinging an additional X-ray beam through another surface of the crystal,

monitoring the X-ray beam for reflections from the atomic planes through the other surface to determine the angle at which the reflections occur, and

averaging the angles at which reflections occur through both the surfaces to determine the axial orientation of the atomic planes in the crystal.

4. In an apparatus for determining the angle of orientation of atomic planes in a crystal relative to a reference surface of the crystal,

means for sequentially focusing oppositely directed X-ray beams for passage into the crystal,

means for angularly displacing the crystal relative to the X-ray beams,

means for detecting Bragg angle X-ray reflections from the crystal,

means for determining the angular positions of the crystal at which Bragg angle reflections occur from the crystal, and

means for averaging the angular positions at which Bragg angle reflections occur to determine the angle of orientation of the atomic planes in the crystal relative to the reference surface of the crystal.

5. The apparatus of claim **4** further including means responsive to said averaging means for directing the crystal to a selected location after the average angular position has been computed.

6. An apparatus for determining the angle of orientation of atomic planes relative to an axis of a reference surface of a crystal comprising:

means for passing sequentially a pair of X-ray beams through the crystal from generally opposite directions,

means for oscillating the crystal about the axis while the X-ray beams are impinging thereon,

means for detecting Bragg angle reflections from the crystal while the crystal is oscillating,

means for determining when the reflections reach a predetermined level of intensity,

means for computing the mean of the angles at which reflections occur from the crystal after the reflections reach a predetermined level of intensity, and

means for averaging the mean angles after the angles are computed to determine the angle which the atomic planes make with the reference surface of the crystal.

7. The apparatus of claim 6 further including means for rejecting the crystal if the Bragg angle reflections do not reach the predetermined level of intensity.

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