The Compact Muon Solenoid Experiment

CMS Note

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Cutting of five PbWO4 crystals in industrial prototype conditions

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Abstract

Five full size $PbWO_4$ crystals were cut at the Bogoroditsk crystal production plant in Russia, using the processing method proposed by CERN - CMA for the mass production of the 110’000 crystals of the CMS Electromagnetic Calorimeter. The machinery, tooling and processing parameters were tested. The resulting crystal surface finish and dimensional accuracy are presented. Improvements in the method are envisaged.

1. PURPOSE OF THE PROTOTYPE CUTTING

This operation took place 13 to 15 November 1996 on a prototype cutting machine identical to the one at CERN. It was intended to validate the tooling set version (III) on real crystals after a preliminary test on marble samples (1), taking the crystal lattice orientation on account for the cutting conditions (2). It had also the purpose of verifying the accuracy of the method (3), the influence of each component of the tooling and of each processing step. A similar test followed at CERN in December 1996 (4).

2. CRYSTAL CHARACTERISTICS

2.1. CRYSTAL INGOT (BOULE) DIMENSIONS

Boules were supplied as shown in fig. 2.1. They were first cut to 240 mm length to match the gypsum mould inner length, then set in the mould and properly positioned.

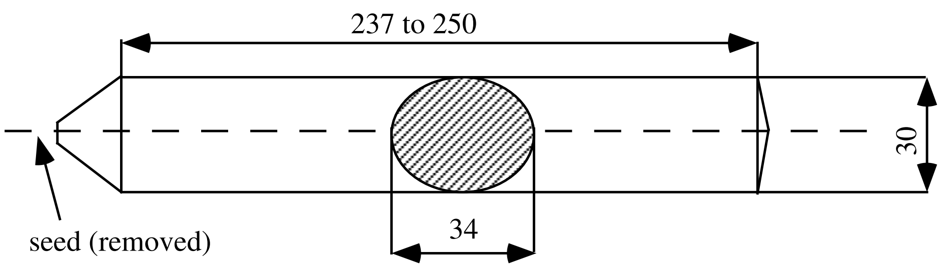


Fig. 2.1. Boule overall dimensions

2.2. CRYSTAL FINISHED DIMENSIONS

The chosen dimensions are for the beam test matrix. The finished crystal is a right pyramid frustum of height 230 mm with square bases 23,8 x 23,8 mm^2 and 20,5 x 20,5 mm$^{2.}$ respectively.

The lapping operation following the cutting removes 50 µ per face; the dimensions for cutting are therefore:

height 230,1 mm = H large base 23,9 x 23,9 mm2= AR x AR small base 20,6 x 20,6 mm2= AF x AF

These dimensions are specified with a target tolerance of: +0; -100 µm

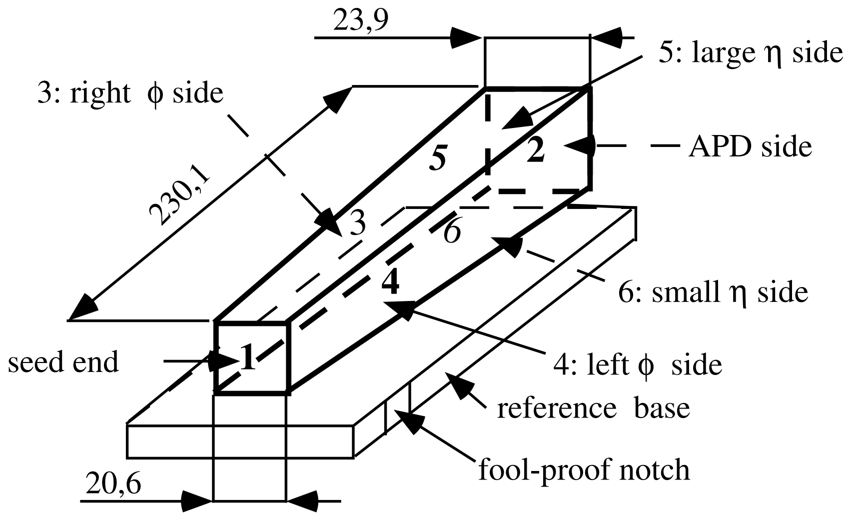


Fig. 2.2. Finished crystal standard dimensions and face numbering convention

2.3. CRYSTAL LATTICE ORIENTATION

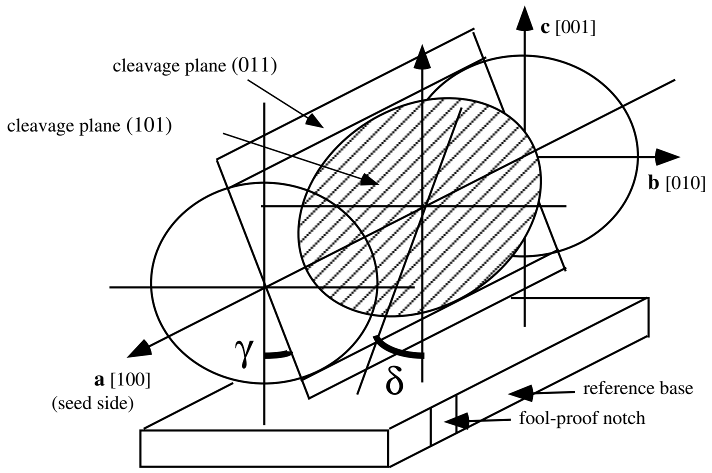


Fig. 2.3. Position of the boule, orientation of the crystal axes and cleavage planes with respect to the reference base. Angles δ and γ of the cleavage planes are typical of the lattice dimensions.

3. THE CUTTING DISK

After a problem of flatness was detected at the first cutting operation on the first disk mounted, a Trifles disk (Ref. No 03) was mounted and used for the 29 remaining cuts. The disk flatness error is plotted in the table below according to fig. 3. After mounting - case (I) - the maximum off-plane is at point B (i. e. the disk, clamped on area R, shows off at point B by 0,044 mm outside the page plane with respect to point F, within the 0,050 mm tolerance). After the completion of the cutting test, another survey was performed, showing that the disk suffered from the incidents mentioned in paragraph 5.1. - case (II)

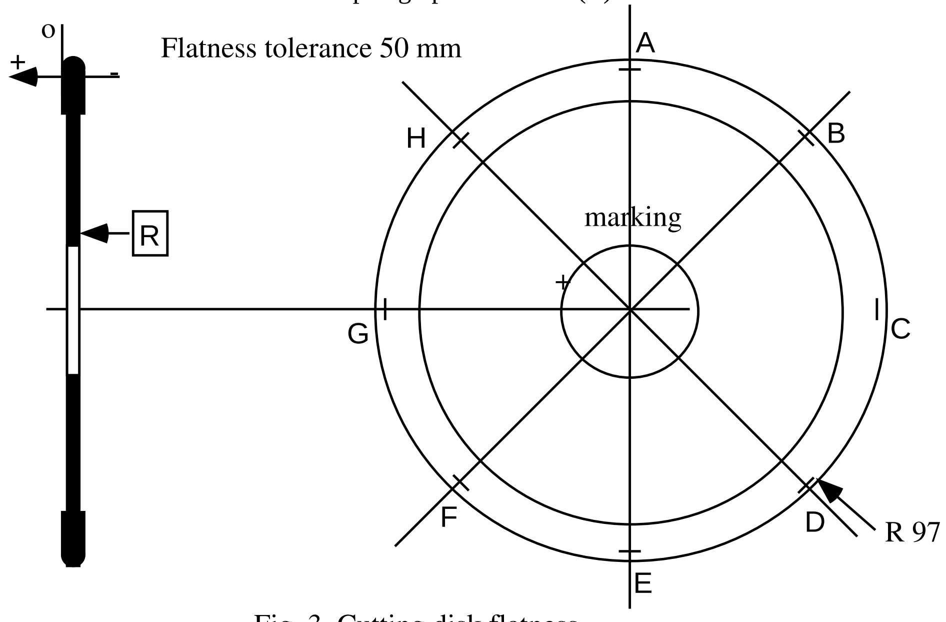


Fig. 3. Cutting disk flatness

Pos	A	B	C	D	E	F	G	H
I	0,020	0,044	0,043	0,031	0,011	0	0,034	0,003
II	0,090	0,050	0	0,020	0,040	0,100	0,120	0,120

4. CUTTING CONDITIONS AND PARAMETERS

Disk rotation speed 2900 rpm

Feed speed 10, 20 and 30 mm / min

Lubrication with special water solution-suspension of pH 9, composition for 10 litres:

- 5 g vaseline oil,
- 25 g sodium carbonate Na_2CO_3 6 H_2O,
- 30 g sodium bromide $Na_2Br_4O_7$ 10 H_2O,
- 60 g sodium phosphate Na_2PO_4 12 H_2O

The lubricant is sent on the two disk faces by 2 nozzles of diameter 1 mm

5. RESULTS AND INTERPRETATION

5.1. GENERAL OBSERVATIONS

The boules had been properly annealed. The cutting direction had been chosen to respect the cleavage plane orientations. As a result the complete cutting cycle on the five boules did not produce any crack.

A problem of ageing happened with the silicate glue used to attach the crystal to the foam rings and the gypsum. The poor adhesion let some crystal chips slide along the cutting wheel at the end of almost every face cutting, forcing the cutting disk sideways and producing some deep scratches. It did not affect the global face geometry and the dimensional measurements are significant. As some chips tended to fall before the face was completely cut, it left some of the end faces corners chipped.

Different feed speeds were used and neither seem to affect the surface finish nor the general geometry.

The cut crystals were shipped to CERN to be measured in the same way as the samples produced at CERN: metrology of dimensions and recording of face roughnesses. After completion of the measurements, the crystals were shipped to Chernogolovka to be used as samples for chemical polishing developments.

5.2. SURFACE FINISH

The roughness of the cut faces was measured on four available samples using a Taylor-Hobson roughness recorder, type Surtronic 3+. Three measurements in longitudinal and three measurements in transverse directions were performed for the face 6 of each sample. Averages and standard deviations are given in the table below:

Crystal	feed speed	face 6	
	mm / mn	Ra [µm]	σ [µm]
2	10	1,90	0,14
3	20	1,66	0,14
4	30	1,89	0,14
5	20	1,90	0,14
all samples	along	1,86	0,13
all samples	across	1,82	0,20

We notice on all samples very similar roughness measurements, and a rather small dispersion. Apart from large scratches mentioned in the previous paragraph, the cutting does not produce any surface pattern following the disk rotation: the Ra measurements in longitudinal and transverse direction produce the same average values. These values are in fact sufficient for the polishing operations to follow.

5.3. METROLOGY RESULTS

The metrology surveys of the cutting disks and of the finished samples were performed by R. Angelloz-Nicoud, MT-MQ. For the samples, the ‘rapports de contrôle’ dated 4 Dec. 1996 (samples 2 to 5) and 9 Dec. 1996 (sample 1) provide the following data:

5.3.1. flatness of each face in µm

The off-plane error (planarity) of the side faces has two main components:

-a twist from the small to the large end (+ sign is for ant-clockwise)

-an inside or outside bend at mid-length (+ sign is for convex shape)

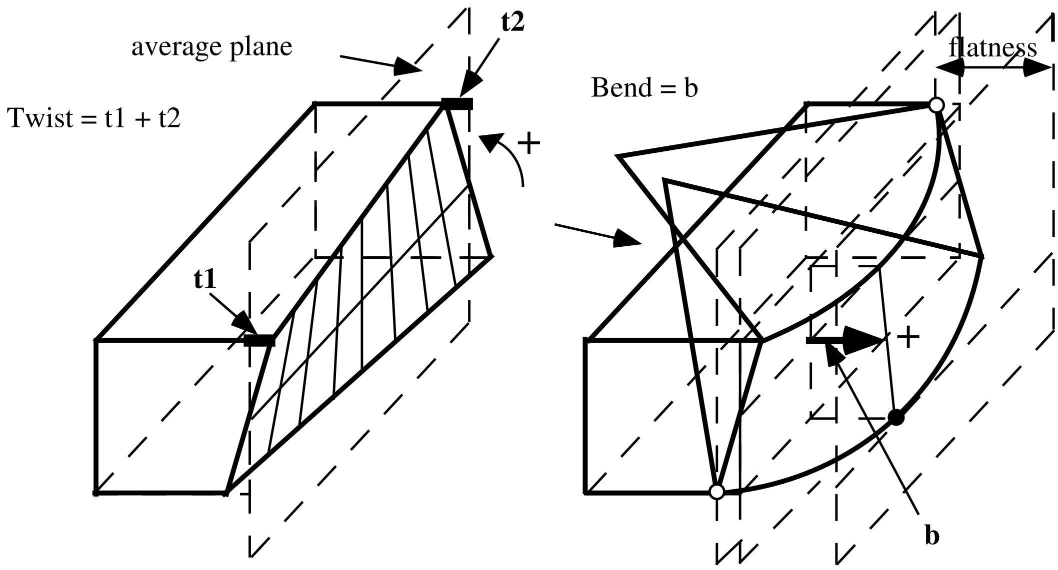


Fig.5.3.1. Schematic of face twist and bend with measuring convention

Crystal face flatness [µm]									
		end faces		side faces					
Crystal (feed speed)		face 1	face 2	face 3	face 4	face 5	face 6	average	st. dev.
1	flatness	2,2	2,2	8,8	6	7,3	5,7	5,4	2,4
(10)	twist	-2	0	0	-3	-3	0	-1,3	1,4
	bend	0	2	8	4	-3	5	2,7	3,5
2	flatness	5,2	7,9	12,6	(29,5*)	14,4	10,6	10,4	3,3
(10)	twist	-2	5	4	(17)	-4	0	0,6	3,4
	bend	5	7	11	(-2)	12	6	8,2	2,8
3	flatness	2,6	2,4	7,3	7,4	7,3	9,0	6,0	2,5
(20)	twist	-3	-1	0	1	-2	-5	-1,7	2,0
	bend	0	-1	5	1	6	7	3,0	3,1
4	flatness	3,6	1,6	12,9	(51,5*)	8,1	9,9	7,2	4,1
(30)	twist	1	1	0	(-)	-4	1	-0,2	1,9
	bend	2	0,5	12	(30)	-3	-8	0,7	6,6
5	flatness	3,3	0,8	6,6	12,1	7,2	9,5	6,6	3,7
(20)	twist	-3	0,5	0	2	-3	1	-0,4	1,9
	bend	0	0,5	5	6	5	-5	1,9	3,8
average	flatness	3,4	3,0	9,6	8,5	8,9	8,9	7,1	
		1,0	2,5	2,6	2,6	2,8	1,7		3,6
st. dev.	twist	-1,8	1,1	0,8	0	-3,2	-0,6	-0,6	
		1,5	2,1	1,6	2,2	0,7	2,2		2,3
	bend	1,4	1,8	8,2	3,7	3,4	1,0	3,3	
		1,9	2,8	2,9	2,1	5,7	6,2		4,8
average	flatness	3,2	1,9		9,0		2,5		
&	twist	-0,35	2,3		-0,8		2,3		
st. dev.	bend	1,6	2,4		4,1		5,5		

The crystal face flatness is much smaller than the disk flatness error (<50 µm). The disk rotation produces a shape envelope which generates the crystal face by translation. Bend and twist can be explained by the disk warping differently during its translation.

We observe an average flatness of 3 µm on end faces. The average twist is not significant, the average bend is +2 µm. On side faces the average flatness is 9 µm. The average twist is not significant, the average bend is +4 µm. These values are much smaller than the off-squareness of the section, and therefore even smaller than the setting error (see next paragraphs). Local defects such as scratches or accidental grooves are not considered. The overall deformation of the face is generally attributed to the disk off-planarity and vibrations.

*) the chip was not kept in place properly because of the poor quality of the glue: it moved along the cutting disk, making it dig into the crystal face.

5.3.2. perpendicularity of end face edges

Crystal		face 3/5	face 5/4	face 4/6	face 6/3	total - 360
1	Small end	90,0590	90,0406	89,8757	90,0247	0
	Large end	90,0595	90,0405	89,8756	90,0243	0
2	Small end	89,8954	90,2060	89,8636	90,0350	0
	Large end	89,8966	90,2062	89,8638	90,0334	0
3	Small end	90,2645	89,8525	90,2534	89,6295	0
	Large end	90,2647	89,8524	90,2533	89,6295	0
4	Small end	89,9858	90,0337	89,9770	90,0035	0
	Large end	89,9863	90,0336	89,9770	90,0031	0
5	Small end	90,1070	90,0565	89,8608	89,9757	0
	Large end	90,1077	90,0564	89,8607	89,9753	0

We have verified the consistency of the angular measurements of table 5.3.2 with the cross section dimensions of table 5.3.4 below (see also fig. 5.3.4). We compared the difference between two opposite sides of a cross section by direct measurement and by angular measurement. The maximal discrepancy is 1 µm.

As an example:

For sample 2, large end, face 3/4, side 6- side 5 = 23,942 - 23,900= 42 µm

Face 3 / face 5 angle = 89,8966° face 5 / face 4 angle = 90,2062°

Sin (face 3 / face 5 angle - 90°) * side 3 = - 43 µm

Sin (face 5 / face 5 angle - 90°) * side 4 = 85 µm

5.3.3. perpendicularity of side faces in degrees

Crystal	face 3/5	face 5/4	face 4/6	face 6/3	total - 360
1	90,0627	90,0435	89,8786	90,0270	0,0118
2	89,8991	90,2090	89,8665	90,0373	0,0119
3	90,2678	89,8553	90,2562	89,6322	0,0115
4	89,9890	90,0366	89,9800	90,0063	0,0119
5	90,1109	90,0594	89,8636	89,9779	0,0118

We verify a very good correspondence between the face angles and the edge angles, which confirms the good flatness of the faces.

N.B. The total of 360,0118° is the sum of the side face angles of the pyramid.

5.3.4. dimensions of cross sections at end faces (+ - 3 µm)

Crystal	small end nominal 20,600				large end nominal 23,900			
	face 3/4		face 5/6		face 3/4		face 5/6	
	side 5	side 6	side 3	side 4	side 5	side 6	side 3	side 4
1	20,505	20,533	16,145*	16,175*	23,836	23,870	19,418*	19,453*
corrected			20,465*	20,495*			23,738*	23,773*
2	20,499	20,535	20,554	20,529	23,900	23,942	23,765	23,735
3	20,534	20,576	20,600	20,562	23,828	23,877	23,852	23,808
4	20,568	20,572	20,524	20,520	23,872	23,880	23,845	23,841
5	20,540+	20,598+	20,508	20,538	23,877+	23,945+)	23,759	23,793
Max.	20,568	20,576	20,600	20,562	23,900	23,942	23,852	23,841
Min.	20,499	20,533	20,524	20,520	23,828	23,870	23,759	23,735
Diff.	0,069	0,043	0,092	0,042	0,072	0,072	0,093	0,106
Average	20,526	20,554	20,546	20,537	23,859	23,892	23,805	23,794
St. dev.	0,027	0,020	0,035	0,016	0,029	0,029	0,043	0,038
Error to average	0,074	0,046	0,054	0,063	0,041	0,008	0,095	0,106
Error due	to sine ruler and zero setting				to zero setting error alone			

*) the cutting wheel was displaced inward instead of outward after setting the zero on the reference sphere. The error is 2 x (displacement TP - boule off-centre to sphere) = 4,320 mm.

+) the base was not in contact with the tool stops, and the operation was repeated, with the small end of the crystal missing a few mm; the dimension mentioned is an extrapolation from the large end with prolongation of the side faces 3 and 4.

*) and +) not taken in the average.

5.3.5. length of samples in millimetres (nominal 230,1 mm, tol + 0 - 100 µm)

Crystal	1	2	3	4	5	Max	Min	Diff	Average	St. Dev.
length	229,873	229,790	229,796	229,785	229,723	229,873	229,723	0,050	229,793	0,048
error	-0,227	-0,310	-0,304	-0,315	-0,377	-0,227	-0,377	0,050	-0,307	0,048

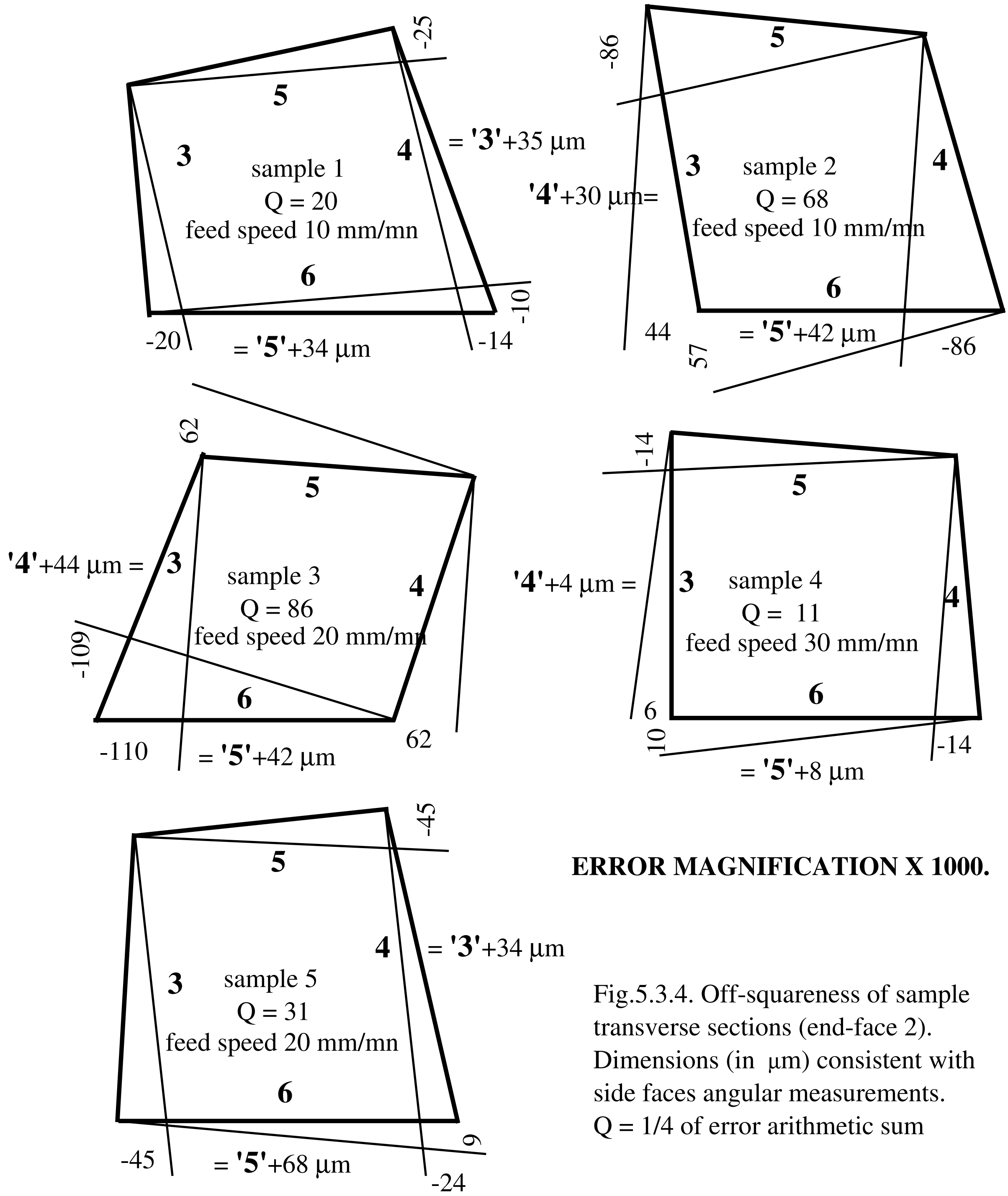


Fig.5.3.4. Off-squareness of sample transverse sections (end-face 2). Dimensions (in µm) consistent with side faces angular measurements.
Q = 1/4 of error arithmetic sum

Fig. 5.3.4 represents the shape of the large end section, with the off-squareness magnified by a factor 1000. The size difference between opposite faces is indicated, as well as an off-squareness factor Q expressed as 1/4 of the arithmetic sum of the four side errors. An algebraic sum would give a misleading information in the case of a lozenge shape (a parallelogram with all sides equal but oblique; sample 3 would have Q = 24 instead of actual Q = 86).

5.4. ZERO SETTING ACCURACY AND REPEATABILITY

The zero setting procedure consists in putting the cutting disk (at its larger off-plane point) in contact with a precision reference sphere. The sphere is secured on a high precision mount identical to the crystal reference base. The sphere position to the tooling corresponds to the crystal nominal position with a precision of 20µm. The contact is confirmed by an electrical device. The disk is then displaced by a computed amount corresponding to the crystal nominal face position (5). As the same sphere reference mount will calibrate every tool in sequence, the error at the zero setting results on the sphere diameter accuracy, on the proper selection of the disk contact area, on the repeatability of the electrical contact, on the precision of contact between the sphere reference base and the tooling stops (and for mass production on the cutting disk wear). An improved disk flatness reduces the uncertainty on the place where it touches the sphere. We compare the expected nominal value and the measured value of the cross section of face 2 near the disk contact to the reference sphere. The cutting of the two faces producing one measured dimension results on two zero settings.

Nominal	N = 23,900	1-N	2-N	3-N	4-N	5-N
face 3/4	side 6	-130	42	-123	-120	(45+)
face 5/6	side 3	(-262*)	-235	-148	-155	-241

*), +) see remarks in parag. 5.3.4.

The processing of the five samples has been performed in the same sequence from 1,through 2, 3, 4,and 5 first for face 1, then this same sequence has been repeated for faces 2, 3, 4, 5 and 6.

5.5. SINE RULER ACCURACY

Verified by comparing for five samples produced with the same setting the difference between corresponding cross section measurements at the two sample ends, and the nominal value. The shimming is performed on a 300 mm sine ruler. The half angle of each face produces a shim value of (3,300 / 2 * 230) * 300 = 2,152. It is rounded to 2,15 mm for practical reasons with a dimension increase on the small end dimension of 6 µm.

For face 3 vs. face 4, the same face of the magnetic table touches identical but inverted piles of shims. As there is a set of tooling stops for each face, their respective parallelism might contribute to the angular error.

For face 5 vs. face 6, opposite faces of the magnetic table touch identical but inverted piles of shims. The same set of tooling stop is used for both faces. In this case the error in parallelism of the magnetic table opposite faces should be considered.

Crystal			face 3/4		face 5/6	
No	Side	Nominal	side 5	side 6	side 3	side 4
1	L	23,900	20,505	20,533	16,145*	16,175*
	S	20,600	23,836	23,870	19,418*	19,453*
	L-S	3,300	3.330	3,337	3,273*	3,278*
2	L	23,900	20,499	20,535	20,554	20,529
	S	20,600	23,900	23,942	23,765	23,735
	L-S	3,300	**3,401**	**3,407**	***3,211***	***3,206***
3	L	23,900	20,534	20,576	20,600	20,562
	S	20,600	23,828	23,877	23,852	23,808
	L-S	3,300	***3,294***	***3,301***	3,252	3,246
4	L	23,900	20,568	20,572	20,524	20,520
	S	20,600	23,872	23,880	23,845	23,841
	L-S	3,300	3,304	3,308	**3,321**	**3,321**
5	L	23,900	20,540	20,598	20,508	20,538
	S	20,600	23,877	23,945	23,759	23,793
	L-S	3,300	3,337	3,347	3,251	3,255
Max		3,300	**3,401**	**3,407**	**3,321**	**3,321**
Min		3,300	***3,294***	***3,301***	***3,211***	***3,206***
Max-Min		0	0,107	0,106	0,110	0,115
L-S average			3,333	3,340	3,262	3,261
standard deviation			0,037	0,038	0,036	0,038
average-to-nominal error			+0,033	+0,040	-0,038	-0,039

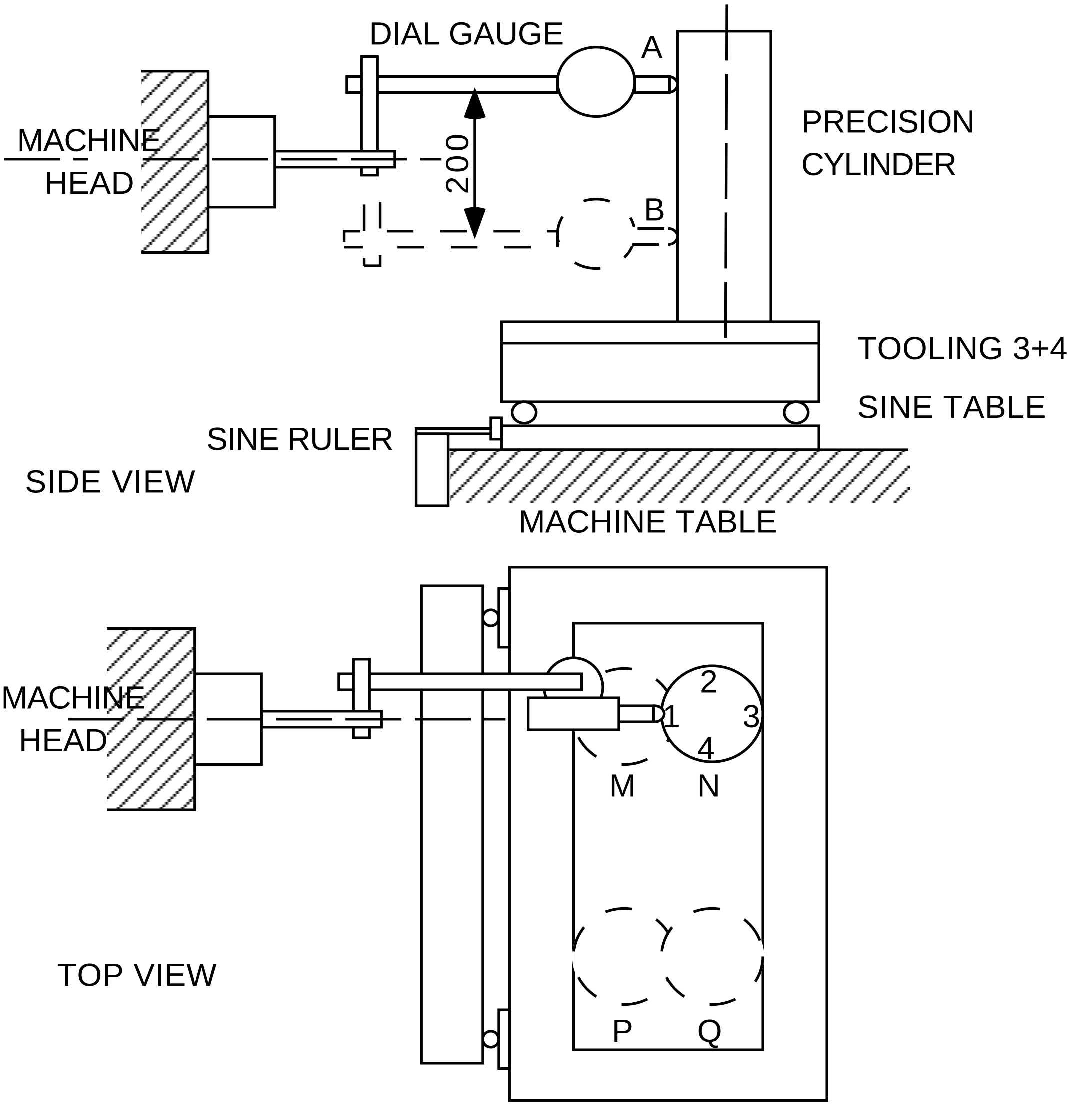
5.6. TOOLING CHECK AFTER TEST

A detailed inspection of the tooling was performed after the test, as soon as the required measurement equipment was made available, to help in error interpretation. The following features were checked:

5.6.1. Flatness of the cutting disk

(cf. paragraph 3, line (II) of the table).

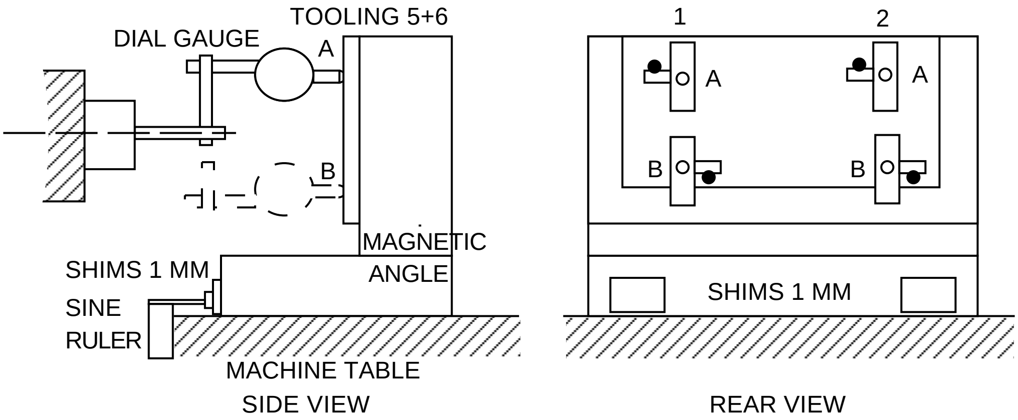
5.6.2. Parallelism of magnetic sine table (cutting operations 3 and 4) with spindle axis.



dial gauge	A				B			
cyl. pos	1	2	3	4	1	2	3	4
M	0	0	0	0	70	70	70	70
N	0	0	0	0	80	75	75	80
P	0	0	0	0	60	60	60	60
Q	0	0	0	0	70	70	70	70

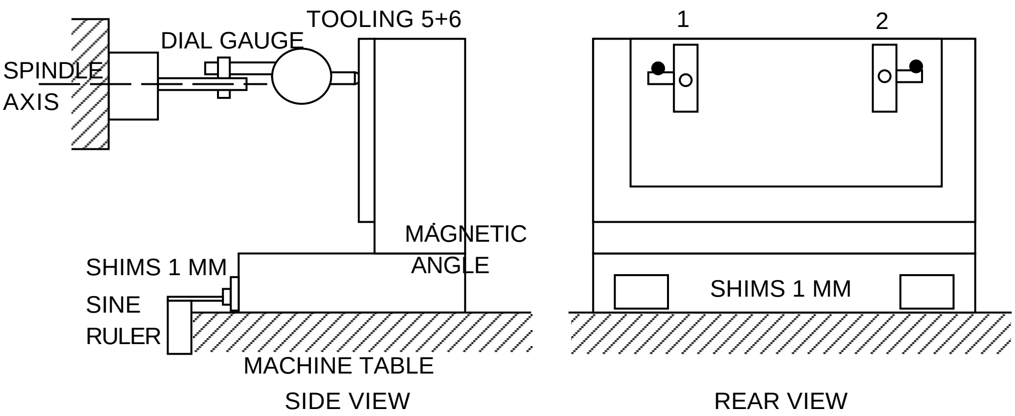
The excellent reproducibility of measurements at the four orientations of the cylinder confirms the reliability of the procedure. One notes a systematic difference between the measurements sets A and B, indicating that the sine table is not correctly shimmed and that the nominal shimming should not be trusted. The average error is 70 µm over a measurement height of 200 mm. This should contribute to a squareness error on the crystal section of 2 * (70 * 23,9 / 200) = 17 µm in excess on face 6. In fact, the average excess on faces 6 is 39 µm, suggesting that the main contribution to this type of error is the disk off planarity caused by chips accidental ungluing.

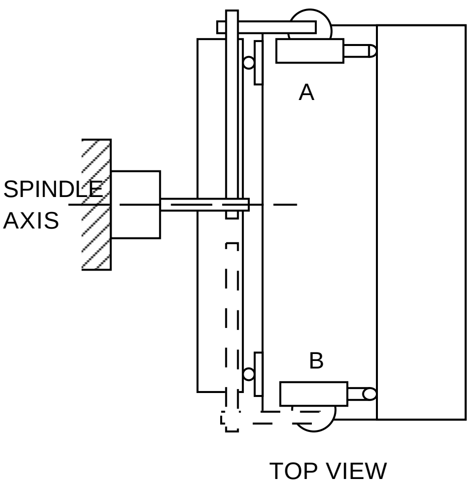
5.6.3. Perpendicularity of magnetic angle table to spindle axis.



This measurement showed no difference between positions A and B produced by the spindle rotation, and between positions 1 and 2 produced by the table translation. The magnetic angle table is therefore perpendicular to the spindle axis better than 20 μm over 100 mm and should not affect the crystal section shape. In fact the squareness error measured on the crystal section as a difference between side face 3 and 4 is randomly distributed, confirming that the main contribution to this error is the disk off planarity caused by chips accidental ungluing.

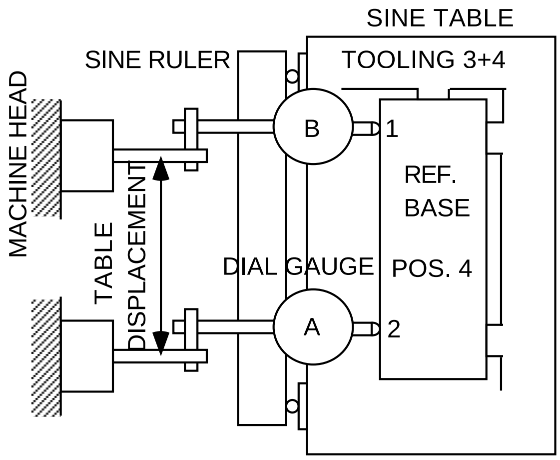
5.6.4. Parallelism of magnetic angle table to translation movement.

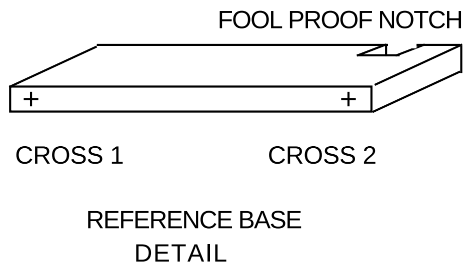




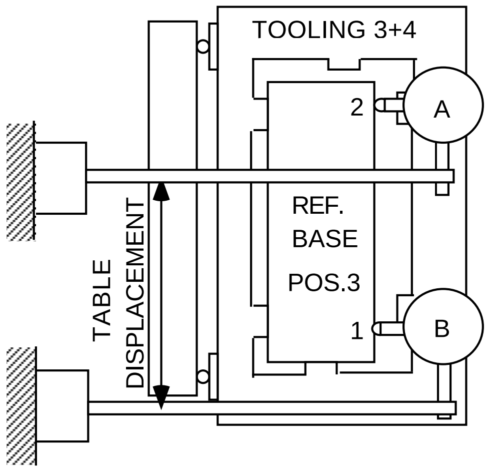
This measurement showed no difference between the two extreme positions of the magnetic angle, either produced by the spindle rotation from A to B, or by the table translation from 1 to 2. The error in taper angle for the couple of faces 5 + 6 should mainly be attributed to the sine ruler.

5.6.5. Reproducibility of reference base contact from cutting position 3 to 4 for the five reference bases.





TOP VIEW



TOP VIEW

tool position	3		4		difference
cross No / base No	1	2	1	2	4-3
1	0	40	0	30	-10
2	0	10	0	20	10
3	0	30	0	20	-10
4	0	10	0	0	-10
5	0	10	0	10	0

There is no systematic difference between respective positions measured in the same way on the five reference bases. The difference amounts to the dial gauge measurement accuracy. This confirms a good repeatability of the positioning concept.

6. CONCLUSIONS

The good performance achieved in this test confirms the validity of the chosen method, even for very anisotropic crystals. We proved that annealed crystals can be safely cut without cracking.

Although some reset performed after a first calibration cut might correct an error in the zero setting, there is still some progress to do in the tooling accuracy. The identified components of the dimensional error are the following:

- tooling positioning repeatability, incl. sine ruler, average 38 µm, maximum 107 µm.
- zero setting drift, average 118 µm, maximum 241 µm.
- off-squareness of the section, average 43 µm, maximum 86 µm.
- side face flatness, average 9 µm, maximum 15 µm.

The combination of these four effects produces a total error average of + - 40 µm (computed 130 µm) and maximal deviations of + - 100 µm to nominal.

To safely reach the +0; -100 µm tolerance, the tooling should be improved after all the components of the error are well identified. The test performed at CERN in December 1996 on five more crystals provide more data and detailed conclusions can be drawn from these two fruitful tests (4).

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