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The Compact Muon Solenoid Experiment

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Cutting of five PbWO4 crystals on the CERN prototype cutting machine

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Abstract

After a similar test performed at the Bogoroditsk Electrochemical Factory in Russia, five full size $PbWO_4$ crystals were cut on the CERN prototype cutting machine, using the processing method proposed for the mass production of the 110’000 crystals of the CMS Electromagnetic Calorimeter. The machinery, tooling and processing parameters were tested, including some improvements from the mentioned Russian test. 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 from 9 to 17 December 1996 on the CERN prototype cutting machine. 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 had been performed at the Bogoroditsk Electrochemical Factory, Bogoroditsk, Tula, Moscow region, Russia, from 13 to 15 November 1996 (4).

2. CRYSTAL CHARACTERISTICS

2.1. CRYSTAL INGOT (BOULE) DIMENSIONS

Five boules were delivered by the Bogoroditsk Electrochemical Factory at the end of October 1996, with the following information:

Crystal No	Weight [g]	Length [mm]	Growth orientation	Remarks
953	1750	247	x	annealed
954	1840	250	x	annealed
955	1750	247	x	not annealed
956	1760	250	x	not annealed
957	1800	237	x	annealed

The boule shape was a cylindroid of oval section terminated by a steep cone on the seed side and a shallow one on the opposite side. The seed side cone had first to be sawed off to match the boule length with the gypsum mould. In spite of all precautions - using a wire saw at a feed speed of 2 mm / min - samples 953 and 954 produced shallow cracks in the boule side faces.

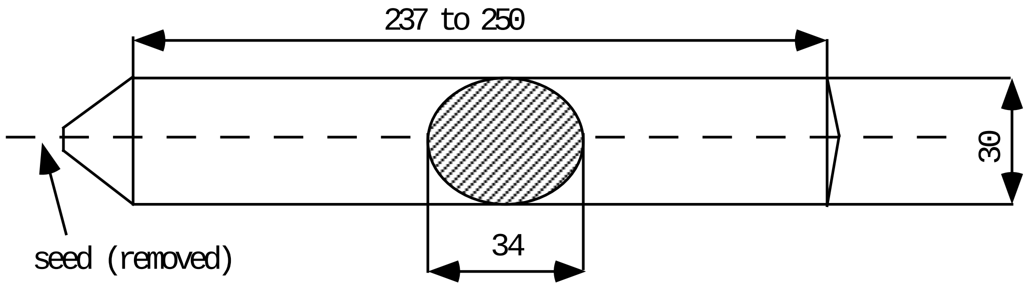


Fig.2.1. Boule overall dimensions

2.2. CRYSTAL LATTICE ORIENTATION

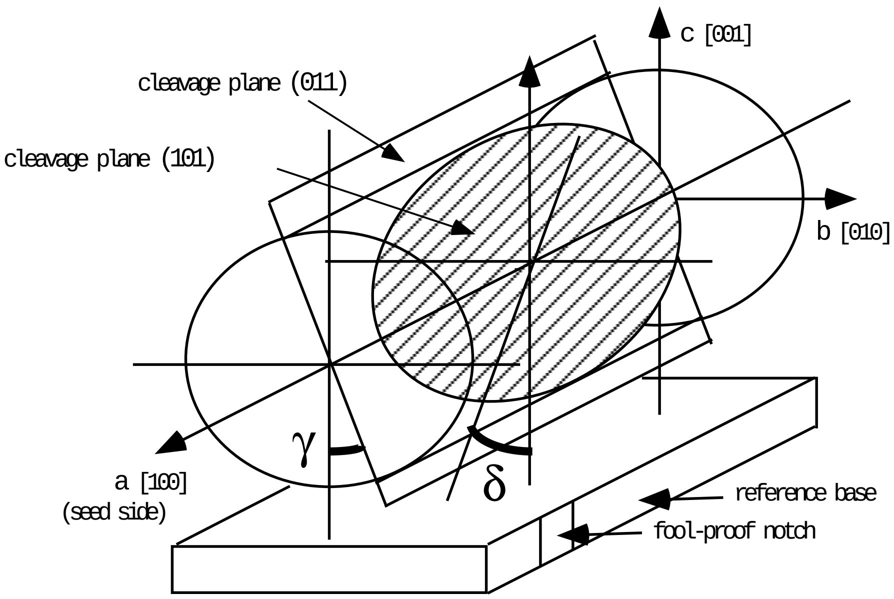


Fig. 2.2. Position of the boule, orientation of the crystal axes and cleavage planes with respect to the reference base. Angles δ and γ of the cleavage planes are typical of the lattice dimensions.

3. THE CUTTING DISK

A Triefus disk ref. D76-MG35640-04 was used for the 30 cuts. The disk flatness error on the marked side (cutting conditions are such that all six faces are produced by the marked side of the cutting disk, on the operator's side) is given on a 97 mm radius, in the table below, before the cutting operations on an inspection tool (I), clamped on the machine spindle (II), after the cutting operations clamped on the machine spindle (III) and on the inspection tool (IV). We observe some deformation from clamping differently on the inspection tool and the spindle, and also some warping induced by tensions from the cutting operation. The average disk thickness at R 97 mm was 1,867 mm before cutting and 1,858 after, and at R 92 mm 1,815 mm before and 1,805 after.

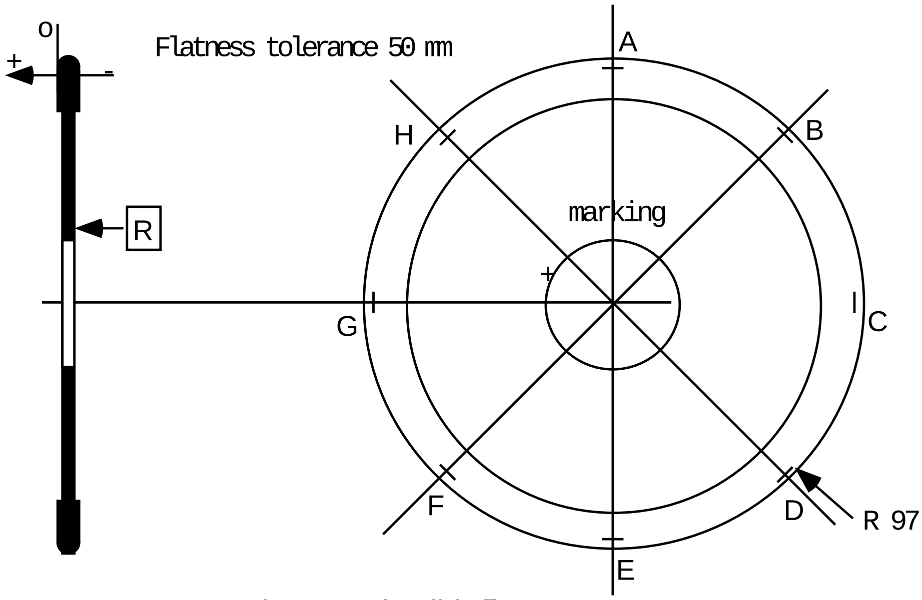


Fig. 3. Cutting disk flatness

Pos	A	B	C	D	E	F	G	H
I	-0,007	0,000	-0,048	-0,027	-0,036	-0,044	-0,038	-0,009
II	-0,07	0,00	-0,02	-0,00	-0,05	-0,04	-0,04	-0,02
III	-0,05	0,00	-0,02	-0,02	-0,01	-0,02	-0,06	-0,04
IV	-0,028	-0,061	-0,114	-0,112	-0,056	-0,021	-0,029	0,000

The disk was balanced dynamically at the working revolution speed, using the balancing head before the cutting operations. The balancing was found unchanged after the test.

4. CUTTING CONDITIONS AND PARAMETERS

Disk rotation speed 2900 rpm (*)

Feed speed 30 mm / min (*)

(*) these conditions had also been applied in the tests performed in November at Bogoroditsk .

Lubrication with deodorised petrol Shellsol T, 2 nozzles of diameter 1 mm

The cut crystal dimensions are those for the test matrix:

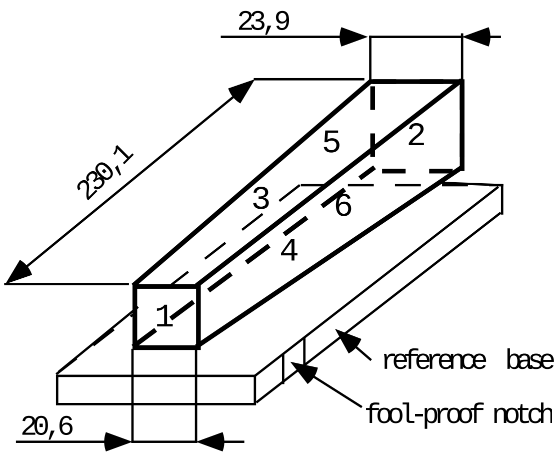


Fig.4. Standard dimensions and face numbering conventions

5. RESULTS AND INTERPRETATION

5.1. GENERAL OBSERVATIONS

The initial cracks observed while preparing the boule samples 953 and 954 were outside the finished volume: the cutting operation did not propagate them and sound crystals resulted. For samples 955 and 956 (not annealed) cracks developed during cutting in the seed end side: for sample 955 (unbroken), the crack is visible from face 1 on 7 mm and from face 5 on 35 mm. For sample 956 (unbroken), the crack is visible from face 1 on 7 mm and from face 4 on 20 mm. Sample 957 has no crack.

The quality of the edges is summarised in the table below. Sizes of edge chips are in mm. Larger chips (ca. 1 mm) tend to start scratches on the adjacent face as if taken by the cutting disk movement. Large chipped corners are visible on samples 955 and 956 (not annealed).

An off-centering of the boule to the finished shape of the order of 1 to 2 mm leaves the original boule surface visible in the form of smooth tapered chamfers up to 4mm. This error will be corrected by a more accurate placing of the boule on the reference base.

Crystal	side edges	front edges	rear edges	off-center edges	front corners	rear corners
953	< 0,5	< 0,3	< 0,3	on face 5 -> 4	2	1
954	< 1	< 0,5	< 1	on face 5 -> 2	0,5	1
955	< 0,5	< 0,3	< 0,3	on face 5 -> 4	4	12
956	< 1	< 0,3	< 0,3	on face 5 -> 4	1	7
957	< 1	< 1	< 0,3	on face 6 -> 3	2	0,5

5.2. SURFACE FINISH

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

Crystal	face 3		face 6	
	Ra [µm]	σ [µm]	Ra [µm]	σ [µm]
953	2,27	0,20	1,51	0,15
954	1,84	0,09	1,49	0,09
955	1,47	0,05	1,53	0,13
956	1,44	0,10	1,79	0,26
957	1,70	0,22	1,60	0,22

We notice on all five samples a different surface finish aspect for the face couples 3-4 and 5-6. For samples 953, 955, 956 and 957 faces couple 3-4 and for sample 954 face couple 5-6 have a fine, very regular but grainy aspect, which produces a glossy reflection at a well defined inclination to a light source. Conversely the other face couples display a much smoother aspect. This has certainly to do with the lattice orientation. Apart from large scratches mentioned in the previous paragraph, the cutting does not produce any surface pattern following the disk rotation: for the same face, the Ra measurements in longitudinal and transverse direction produce the same average values. In fact we observe for sample 953 face 3 this grainy feature with the largest apparent grain size corresponding to the largest measured Ra value of 2,27 µm. This value is 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. The measurement accuracy is + - 3 µm. For the samples, the 'rapport de contrôle' dated 19 Dec. 1996 provides 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)

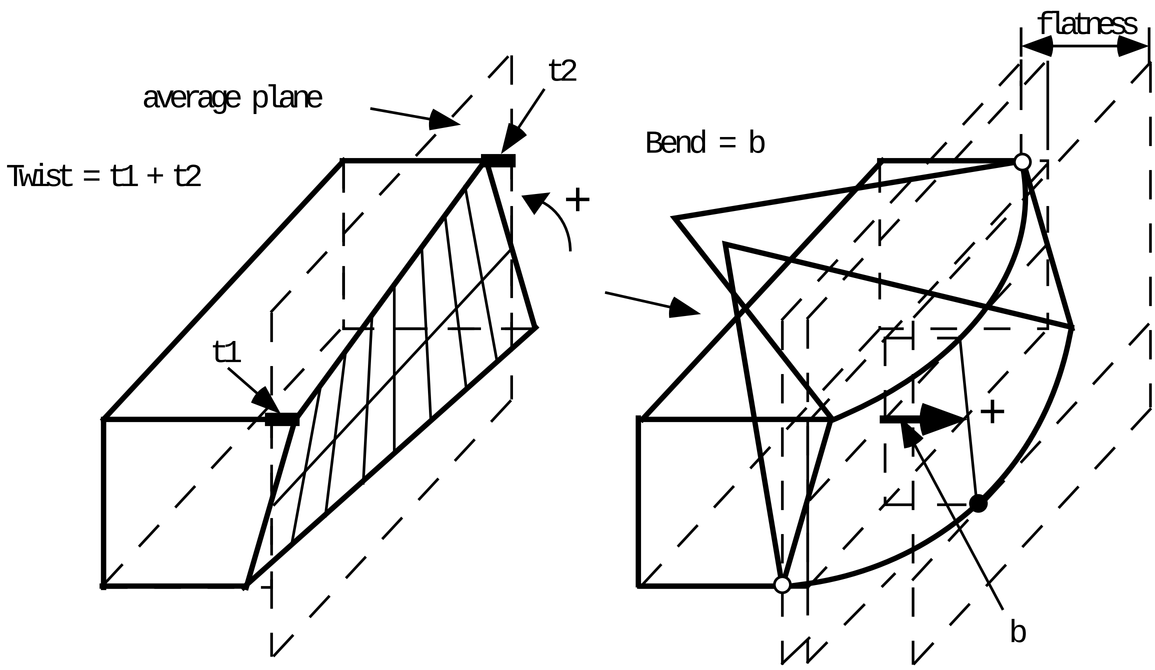


Fig.5.3.1. Schematic of face twist and bend with measuring convention

Crystal face flatness [µm]							
Crystal		face 1	face 2	face 3	face 4	face 5	face 6
953	flatness	20	14	10	6	6	6
	twist	-10	6	-6	0	2	0
	bend	-5	9	2	2	2	-1
954	flatness	5	6	5	11	11	10
	twist	-4	-3	-1	-3	-2	0
	bend	1	-1	-1	-4	6	6
955	flatness	17	2	9	13	30	21
	twist	-2	-1	1	-3	-15	-10
	bend	-4	1	4	3	10	8
956	flatness	15	2	26	19	16	7
	twist	4	-2	0	-2	6	-3
	bend	0	-1	12	-12	-10	-4
957	flatness	4	17	10	17	13	13
	twist	-4	-16	-4	0	6	0
	bend	2	-4	6	6	-4	-6
Average	flatness	12,2 6,5	8,2 6,2	12 7,2	13,2 4,6	15,2 8,1	11,4 5,4
St. Dev.	twist	-3,2 4,5	-3,2 7,1	-2 2,6	-2 2,6	-0,6 7,8	-4,5 0,9
	bend	-1,2 2,8	0,8 4,4	4,6 4,4	-1 6,4	0,8 7,1	0,6 5,5
Average	St. Dev	end faces		side faces			
	flatness	10,2	6,7	13,0	6,6		
	twist	-3,2	6,0	-1,7	4,6		
	bend	-0,2	3,8	1,3	6,3		

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 12 µm on every face, with an average twist of -2,6 µm and an average bend of +0,8 µm.

These values are much smaller than the off-squareness of the section, and therefore even smaller than the setting error (see next paragraphs).

5.3.2. perpendicularity of end face edges in degrees

Crystal	End	face 3/5	face 5/4	face 4/6	face 6/3	total - 360
953	Small end	90,0570	90,0000	89,9852	89,9578	0
	Large end	90,0576	89,9997	89,9849	89,9578	0
954	Small end	90,0765	90,0333	89,9404	89,9498	0
	Large end	90,0775	90,0333	89,9404	89,9488	0
955	Small end	89,9439	90,1534	89,9418	89,9609	0
	Large end	89,9445	90,1533	89,9418	89,9603	-0,001
956	Small end	89,9735	90,0808	89,9408	90,0048	-0,001
	Large end	89,9728	90,0812	89,9412	90,0049	0,001
957	Small end	89,8632	90,1273	89,9389	90,0707	0,001
	Large end	89,8617	90,1274	89,9380	90,0718	-0,011

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. 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 953, large end, face 3/4, side 6- side 5 = 23,921-23,897 = 24 µm

Face 3 / face 5 angle = 90,0576° face 5 / face 4 angle = 90,0000°

Sin (face 3 / face 5 angle - 90°) * side 3 = 23,90 µm

Sin (face 5 / face 5 angle -90°) * side 4 = 0

5.3.3. perpendicularity of side faces in degrees

Crystal	face 3/5	face 5/4	face 4/6	face 6/3	total - 360
953	90,0602	90,0028	89,9880	89,9615	0,0125
954	90,0800	90,0364	89,9435	89,9524	0,0123
955	89,9470	90,1565	89,9449	89,9036	0,0120
956	89,9752	90,0844	89,9443	90,0082	0,0121
957	89,8660	90,1302	89,9419	90,0742	0,0123

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 360,0123° is the sum of the side face angles of the pyramid.

5.3.4. dimensions of cross sections at end faces in millimetres

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
953	***20,455***	20,475	20,427	***20,432***	**23,897**	23,921	***23,770***	***23,777***
954	**20,535**	**20,575**	***20,425***	20,434	23,883	**23,929**	23,779	23,790
955	20,498	20,533	20,586	20,551	23,830	23,871	23,900	23,860
956	20,480	20,500	20,560	**20,552**	***23,798***	23,821	23,938	23,928
957	20,471	***20,467***	20,560	20,536	23,813	***23,809***	**23,958**	**23,930**
Max.	20,535	20,575	**20,586**	20,552	23,897	23,929	23,958	23,930
Min.	20,455	20,467	20,425	20,432	23,798	23,809	23,770	23,777
Diff	0,080	0,108	0,161	0,120	0,099	0,120	0,188	0,153
Average	20,488	20,510	20,512	20,501	23,844	23,870	23,869	23,857
St. dev.	0,027	0,040	0,071	0,056	0,039	0,050	0,079	0,065
Error to average	-0,112	-0,090	-0,088	-0,099	-0,056	-0,030	-0,031	-0,043
Error	sine ruler and zero setting				zero setting error alone			

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

Crystal	953	954	955	956	957	Max.	Min.	Diff	Average	St. dev.
length	229,848	229,850	229,891	229,835	229,908	229,908	229,835	0,073	229,866	0,028
error	-0,252	-0,250	-0,209	-0,265	-0,192	-0,192	-0,265	0,073	0,234	0,028

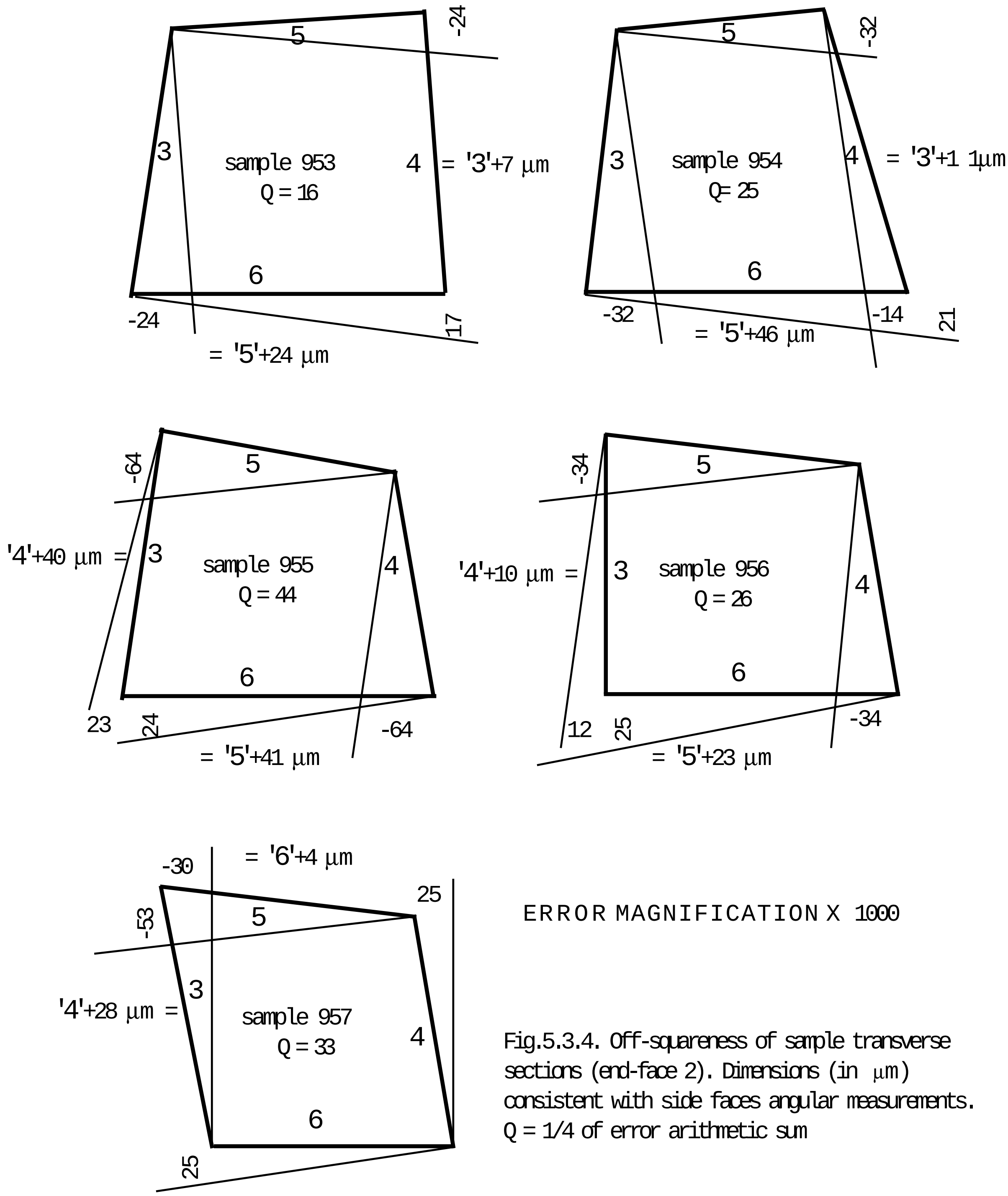


Fig.5.3.4. Off-squareness of sample transverse sections (end-face 2). Dimensions (in μm) consistent with side faces angular measurements. Q = 1/4 of error arithmetic sum

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 957 would have Q = 8 instead of actual Q = 33)

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	953-N	954-N	955-N	956-N	957-N
face 3/4	side 6	21	29	-29	-71	-91
face 5/6	side 3	-130	-121	-121	38	58

The processing of the five samples has been performed in the same sequence from 953 through 954, 955, 956 to 957 first for face 1, then this same sequence has been repeated for faces 2, 3, 4, 5 and 6.

For face 3/4 distance, we observe a regular decrease from 21 µm above nominal to 91 µm below nominal.

For face 5/6 distance, we observe a regular increase from -130 µm below nominal to 58 µm above nominal.

A regular wear of the cutting disk would produce an increase of both mentioned dimensions, which is not the case. We have observed a disk wear of 10 µm for the processing of 30 faces, which cannot account for a drift of more than 100 µm per face. From our past experience, we assume that most of this wear should correspond to the ‘ breaking-in ’ of the disk surface, i. e. an effect in the first minutes of operation. We have observed on the spindle a maximal disk deformation of 40 µm between before and after cutting (cf. parag. 3). Although important, it is not consistent with the observed drift.

We have observed after cutting some friction marks on the disk core as if the core plane was protruding on the abrasive rim plane.

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
953	L	23,900	23,897	23,921	23,770	23,777
	S	20,600	20,455	20,475	20,427	20,432
	L-S	3,300	**3,442**	**3,446**	3,343	3,345
954	L	23,900	23,883	23,929	23,779	23,790
	S	20,600	20,535	20,575	20,425	20,434
	L-S	3,300	3,348	3,354	3,354	3,356
955	L	23,900	23,830	23,871	23,900	23,860
	S	20,600	20,498	20,533	20,586	20,551
	L-S	3,300	3,332	3,338	***3,314***	***3,309***
956	L	23,900	23,798	23,821	23,938	23,928
	S	20,600	20,480	20,500	20,560	20,552
	L-S	3,300	***3,318***	***3,321***	3,378	3,376
957	L	23,900	23,813	23,809	23,958	23,930
	S	20,600	20,471	20,467	20,560	20,536
	L-S	3,300	3,342	3,342	**3,398**	**3,394**
Max		3,300	3,442	3,446	3,398	3,394
Min		3,300	3,318	3,321	3,314	3,309
Max-Min		0	0,124	0,124	0,084	0,085
L-S average			3,356	3,360	3,357	3,356
standard deviation			0,044	0,044	0,029	0,029
Average-to-nominal error			+0,056	+0,060	+0,057	+0,056

In fact we notice the same average for the error in the two cases: although the contact between the magnetic table, the shims and the sine ruler touches was carefully checked - a 1 mm shim was placed at the zero side to make sure there was a good contact, and the opposite shimming was conversely increased by 1 mm too - the same average error may be explained by an elastic deformation of the shim pile and the sine ruler itself, that we checked. The magnetic table was removed and put back to contact with the sine ruler, with and without the standard shimming, with and without shock when coming to contact. In the case without shim, a 50 µm metal foil was inserted to ensure a good contact. We noticed a maximal error of 20 µm on the 3,15 mm shim side and 10 µm on the 1 mm shim side. Without shims no error was measured. This rules out an elastic deformation of the sine ruler and strongly indicates that precision hard metal shims should replace the present ones. The measured effect of 20 µm does not explain the error to its full extent.

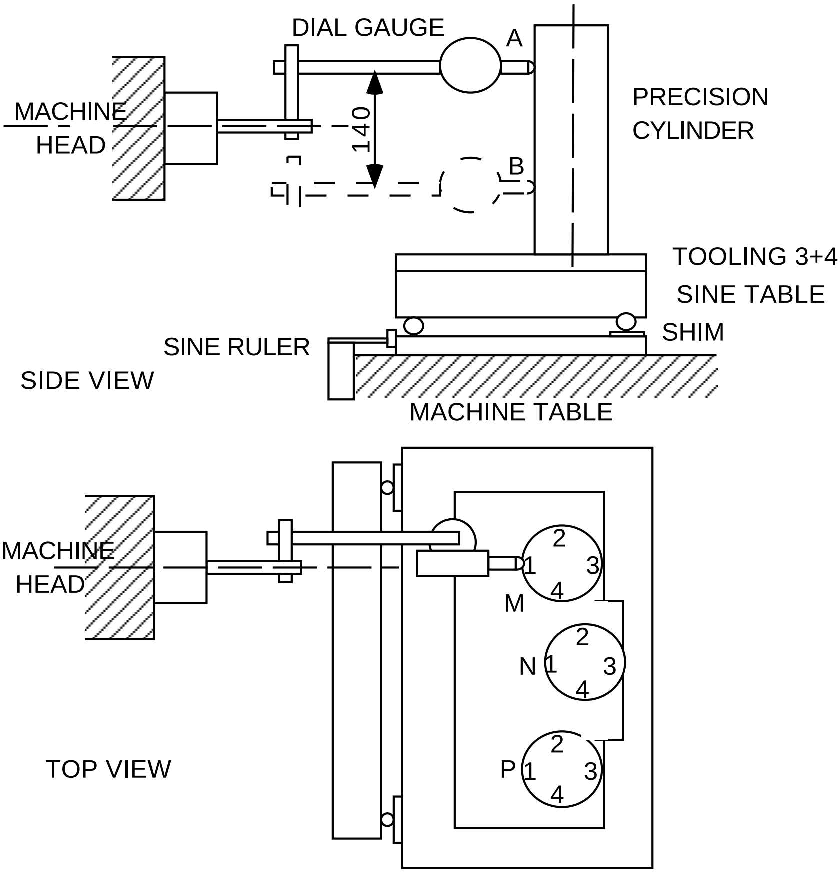
5.6. TOOLING CHECK AFTER TEST

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, lines (III) and (IV) of the table.

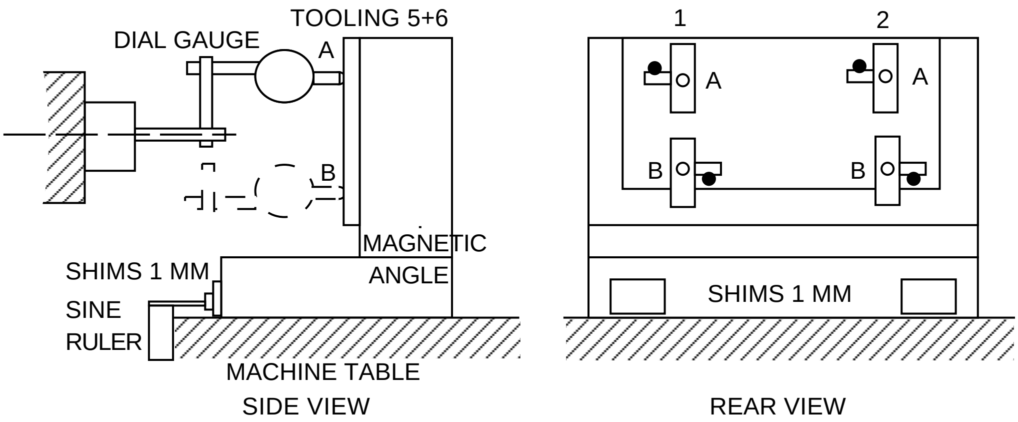
5.6.2. Parallelism of magnetic sine table (cutting operations 3 and 4) with spindle axis.



dial gauge		A				B			
	cyl. pos	1	2	3	4	1	2	3	4
I	M	0	0	0	0	80	85	90	88
	N	0	0	0	0	80	80	75	85
	P	0	0	0	0	90	80	75	80
II	M	0	0	0	0	25	20	20	25
	N	0	0	0	0	20	20	15	20
	P	0	0	0	0	25	20	15	20

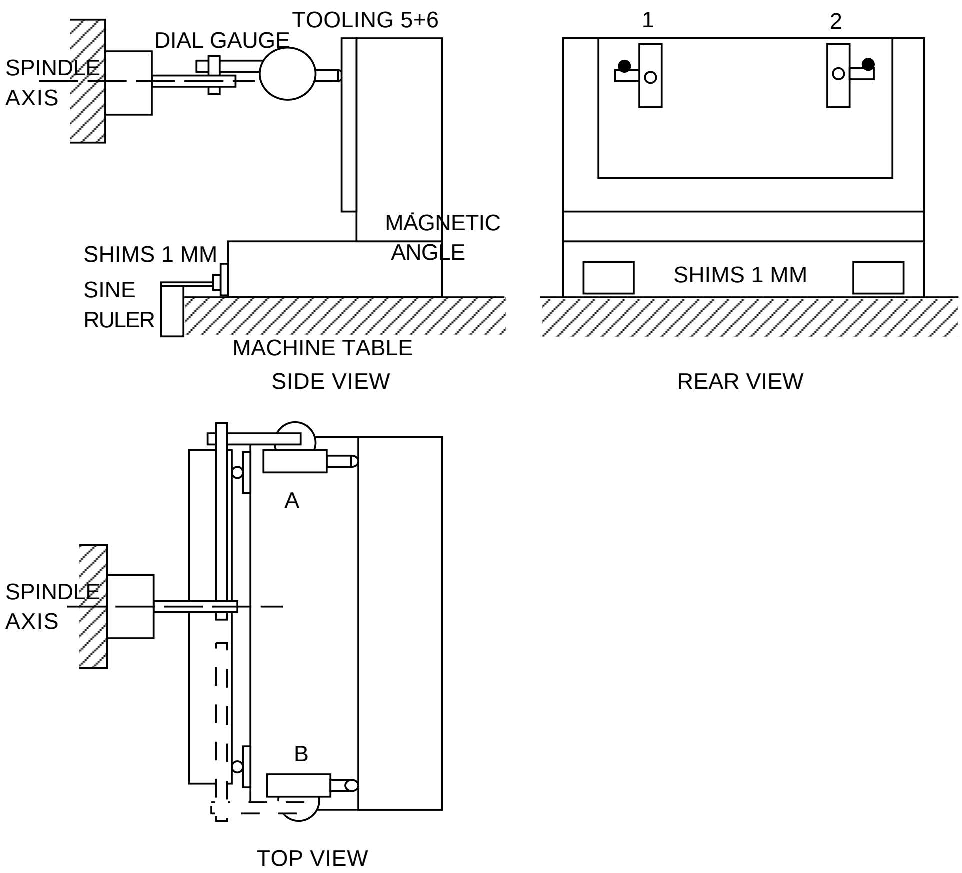
The set of measurement (I) was performed after the cutting test. The set of measurement (II) was performed after a correction of the sine table shimming. In all cases, the excellent reproducibility of measurements at the four orientations of the cylinder confirms the reliability of the procedure. In (I), 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 82 µm over a measurement height of 140 mm. This should contribute to a squareness error on the crystal section of 2 * (82 * 23,9 / 140) = 28 µm in excess on face 6. In fact, the average excess on faces 6 is 26 µm. The shimming is corrected accordingly, replacing the 3 mm shim by a pile of 2,95 mm. The set of measurement II is performed after the correction. The 20 µm average error might be corrected by reducing the shimming to 2,94 mm. Further cutting tests should confirm that this correction was appropriate.

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.

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.

6. CONCLUSIONS

This test confirms the good performance of the test performed at Bogoroditsk in November 1996. In particular, 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 57 µm, maximum 146 µm.

- zero setting drift, average 40 µm, maximum 130 µm.

- off-squareness of the section, average 30 µm, maximum 44 µm.

- face flatness, average 12 µm, maximum 30 µm.

The convolution of these four effects produces a total error average of -70 µm (computed 77 µm) with a standard deviation of 64 µm, and maximum deviations of -175 µm and +58 µm to nominal.

To safely reach the +0; -100 µm tolerance, we plan the following developments:

a- the edge sharpness will be improved by placing the disk in a deeper position, to avoid shallow cutting incidences along the lower edges, especially faces 5/4 and 6/4 at cutting of faces 5 and 6. Scratches coming mostly from edge chipping should be reduced accordingly.

b- the disk geometry made big progress by tighter tolerances and collaboration with manufacturers. The wear observed on the disk is about 10 µm, probably more breaking in than actual wear, to be followed on larger number of cuts. The disk deformation (about 40 µm) is more serious and should be investigated.

c- additional foam pieces glued along the boule in correspondence with the crystal edges will be useful to protect the disk outer part from pulling gypsum swarf into the cutting groove, impairing surface finish and maybe also precision.

d- for the tapering angle, the sine ruler shimming must use hard metal precision shims to avoid a spring effect when the magnetic table is put in place.

e- for dimensions between faces 3 and 4, the contact area of the tooling stops should be reduced so that each reference base will touch exactly at the same areas on the 2 machining positions, and these areas will be the same as for the sphere holder base. A solution is to replace the rectangular contact areas by precision hard steel balls. The modification to the tooling will be performed with the tool on the magnetic table, taking reference on the table reference rectified sides.

f- for dimensions between faces 5 and 6, the matching of the reference base lower face with the vertical magnetic table face must be optimised.

f.1- the composite aluminium-steel reference bases will be abandoned because of the limited contact area.

f.2- on the plain whole steel reference bases, the lower face will be partitioned into three limited areas to make sure that the same contact is maintained on all toolings.

f.3- the vertical magnetic table working face will be inspected to check planarity.

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