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DRAG MEASUREMENTS IN TUBULAR STRUCTURE ELEMENTS. PART 3: EFFECT OF DIAMETER AND SURFACE STRUCTURE ON THE DRAG OF CYLINDRICAL TUBES

G. Schulz and F. Hayn

Translation of "Widerstandsmessungen an Systemteilen von Rohrkonstruktionen. Teil 3: Einflub des Durchmessers und der Oberflachenstruktur auf den Widerstand von Zylindrischen Rohren," Deutsche Versuchsanstalt fur Luft- und Raumfahrt, Report no. DVL 1-NK-I-68-34, April 1968, pp. 1-37

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DRAG MEASUREMENTS IN TUBULAR STRUCTURE ELEMENTS
PART 3: EFFECT OF DIAMETER AND SURFACE STRUCTURE ON THE DRAG OF CYLINDRICAL TUBES

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This report describes measurements on cylinders (tubes) of different/ diameters and different surfaces with transversal flow. Measurements were carried out under a contract with the Comite International pour l'Etude et le Developpement de la Construction Tubulaire (CIDECT), (International Committee for the Study and Development of Tubular Structures), Paris, in the subsonic wind tunnel of the German Test Center for Aeronautics and Space in Porz-Wahn in several short periods during September, October and November, 1967 and February, 1968.

The measurements were carried out at Reynolds numbers between 0.5 by 10-5 and 1.7 by 10-6. The main purpose of these experiments was to obtain more exact knowledge on the effect of the diameter and the surface condition on the critical Reynolds number and the supercritical drag.

To avoid effects of form defects of cylinders on the drag and the critical Reynolds number, turned and polished tubes, not the rolled ones like in the first test section were used. The various surfaces were produced by painting and pasting.

The Reynolds number was brought to the highest achievable value in the German Test Center as regards diameter and velocity of the wind.

These investigations are a continuation of earlier measurements on tubes, on a tube joint and on a section of a lattice post. These earlier results were published in the reports AM 506 /1/ (= new number 1-NK-I-66-19 and AM 507 /4/ (= new number 1-NK-I-67-30). Translations of both reports into English exist /2/, /5/. The first report was also translated into French /3/.

*Numbers in margin indicate pagination in the foreign text.

1. Statement of the Problem /4

Earlier measurements on cylinders (tubes) of 70 and 108 mm diameter /1/, /2/, /3/ show that the critical Reynolds numbers of cylinders depends as we know not only on the surface roughness but also on the diameter. Some smaller measurement programs by other others /6/, /7/, /8/ allowed the assumption that the critical Reynolds number reaches asymptotically a certain upper limit with decreasing surface roughness or with increasing diameter. This hypothesis was confirmed by the measurements carried out. Unfortunately in the earlier investigations the dependence of the critical Reynolds number was covered by insufficient reproducibility and inversely.

By virtue of a contract with the International Committee for the Study and Development of Tubular Structures (CIDECT), Paris, measurements were therefore carried out on five cylinders of different diameters (from 70 to 293 mm diameter). The surface was also made to vary on these five smooth turned tubes.

The purpose of the measurements is the same as for the previous measurements for the same client /1/, /2/, /3/, /4/, /5/: the knowledge for the calculation of the windload on tubular structures was to be extended.

2. Designations /5

The main dimensions of the models are given in Figure 1 (page B1).

To calculate the nondimensional coefficients (Section 6) the following designations were chosen:

v	Speed of flow (m/s)
q	Dynamic pressure in the wind tunnel throat (kp/m^2)
ρ	Density of air (kp by sec^2/m^4)
ν	Kinematic viscosity (m^2/s)
d	Tube diameter (m)
$Re = \frac{v \text{ by } d}{\nu}$	Reynolds number
l	Tube length (m)
$F = d$ by l	Reference area (m^2)
D	Diameter of the end discs (m)

$\frac{D}{d}$	Diameter ratio of end disc to tube
W	Air drag in the direction of the wind (kp)
$cw = \frac{W}{q\ \bar{b}y\ F}$	Drag coefficient
h	Height of an individual unevenness (μm) + above level - below level

3. Model Description /6

The five models corresponded in the design structure entirely to those of the first report /1/. They were suspended on the mechanical fixed component balance of the DVL wind tunnel by means of a rigid lined shaft. They were provided just as in that case with thin circular end discs which arranged with sufficient precision for a bidimensional flow on the tubes. To this end according to /1/ it is sufficient to have a diameter ratio of D/d = 4. To this end special measurements have been carried out in /1/. The problem could be considered as completely solved and we need not discuss it further here.

Five different tube diameters were chosen to obtain for the first time reliable information on the effect of the diameter. The main dimensions of the models are found in Figure 1. The maximum diameter is 293 mm. Although the Reynolds number was to be as large as possible, it would hardly have been worthwhile choosing it even larger, since then the cross-section blocking of the tunnel throat by the model would have been too great and the measurements would have been falsified.

On the other hand there would have been no purpose in selecting the minimum diameter less than 70 mm, since then the critical Re number could no longer have been reached. In the diameter range thus chosen of 70 to 293 mm the five diameters were distributed in somewhat geometrically uniform division.

The aerodynamic coefficients of the five cylinders were measured with different surface quantity. Here the following surface structures were produced.

a) Smooth polished surfaces without lacquer (Table 3, Diagram 11).
b) Surfaced just as (a) but lacquered (with few disturbing elements, Table 4, Diagram 12).
c) Surfaced as for (a) but lacquered (with many disturbing elements).
d) Surfaced just like (a) but with "protective paint".
e) Surfaced just like (a) pasted with a point pattern tapestry.

To relate the aerodynamics with the surface structure, the latter must be recorded in its fine structure.

Practically occurring surfaces usually have simultaneously two types of surface defects, specifically:

1) Production effects (for in the tube for example lack of roundness and diameter effects). /7
2) Unevennesses.

Under some circumstances the former is a long wave defect of large amount, the second are "short wave" microstructures in the form of small elevations (grains, dust) and depressions due to different causes (turning grooves, scratches in the lacquer, rust among others). Both types of defects affect the aerodynamic forces.

Earlier investigations showed that the unsystematic defects of the first type can cover absolutely and falsify the systematic nature of the second type. To avoid this drawback we use not rolled but exactly turned and polished tubes. In the latter therefore the defects of the first type are completely avoided and differences in the forces of flow can be attributed without any reservations to the effect of the microstructure of the surface as well as to the diameter (that is the absolute model size!)[2]

The fine structure of the surface was recorded in the surfaces a, b and e in all its details. Since the production of the surface is in no way related to the tube diameter, it could be assumed from the

2The two tubes described in /1/ were rough from rolling and had unevenness up to 1.5 percent of the diameter.

beginning that the absolute roughness (but not necessarily the relative one) was independent of the diameter. For the surface e (tapestry point backing) this is immediately illuminating. Moreover the measurement of this surface is simple. Only 3 lengths established specifically its fine structure; distance of point (division) point diameter and point height (see Figure 5).

For the two surfaces a and b because of the smallness and the statistical distribution of the individual distrubances the recording of position size and especially the height is more difficult. It is immediately apparent that the measurement of only a few points can take place, since the surfaces of the cylinder are of the order of magnitude 10-6 mm^2 which must be reviewed for individual disturbances up to 10--3 mm height. This outlay of work would have been quite disproportionate to the informative value, therefore for each tube and each of the two types of surfaces only 100 mm^2 were recorded in the hopes that these parts could be considered representative for the entire tube.

It was further to be noted that the surface photography had to be carried out in a <u>nondestructive</u> manner both with regard to the microstructure and for the whole tube. Therefore there was <u>no</u> question of taking a specimen for the examination under the microscope. Because of the necessary strong enlargement (100 to 200 times) however we could not do without the microscope. Therefore a sheet printing method was chosen (the Transcopy method of the Struers Company, Copenhagen). The small plastic films contain after printing all the elevations and depressions.[3] The disturbances were recorded in tabular form (Tables 3 and 4) and plotted finally as frequency distributions in Diagrams 11 and 12. These figures showed a percentage frequency of a point disturbance as a function of its <u>height</u> h. In this connection n is the observed number of the disturbances of a certain tube, N the total number of observations.

For the surface (a) 47 percent of the studied areas (1 mm^2 each) are <u>free</u> from disturbances and 88 percent of all the disturbances are less than plus or minus 2 μm. Such a surface is aerodynamically smooth

[3] We were supported in this study by the DVL Institute of Material Science in Porz-Wahn.

for all cylinders and wind speeds. The surface (b) is clearly poorer. The areas without disturbances represent the components of only 36 percent; even disturbances up to 10 μm and more occur. About 70 percent of the disturbances are less than 2 μm.

It is striking that for the surface (a) all five cylinders have nearly the same curve. The conclusion may be drawn that although only about one ten thousandth of the surface was measured, the results could be considered obviously as representative for the whole cylinder each time (for the surface (b) the mutual turn of the cylinders was somewhat greater).

If the surface (e) is also represented in this manner it may be noted that there are no "depressions". About 70 percent of the surface are without disturbances and are several hundred μm high!

Some care was required by the application of the tapestry pattern. This pattern was chosen to obtain as compared with the smooth state of the tube a clearly distinguished contrast which also showed no lack of hardness or diameter defects, but on the other hand strong and reproducible roughness. These requirements could in our opinion be achieved only by applying a foil. To this end plastic foil and paper with geometrically /9 simple plastically emphasized pattern was suitable. The tapestry satisfies this objective and could be obtained without any waiting time. It was pasted by means of tapestry glue to the model already suspended in the tunnel throat, dried beforehand with a weak current of air and measured immediately afterwards.

The whole occupation density of the individual disturbances is also interesting. For the surface (a) it is 0.532 (mm^{-2}), for the surface (b) 0.64 (mm^{-2}).

4. Implementation of the Tests

All five cylinders were studied with all the surface structures in close increments over the entire range of speed of the DVL wind tunnel. To achieve the largest possible Reynolds number, the tunnel was each time operated for a short time with an overload (speeds up to 94 m/s).

Only the drag and not the lateral force was measured. The tunnel turbulence was about 0.05 to 0.06 percent (calibration measurement).

The three largest cylinders (from 156 mm diameter) tended to oscillations starting from speeds of about 40 m/s (frequencies of a few Hertz). They were therefore attached with lateral wires which did not affect the measurement of drag.

Here we may also put forward the consideration on the maximum achievable Re numbers on cylinders: in any case the incompressible flow (flow with small mach numbers) have to be established since the effect of the natural wind would never cause effects of compressibility.

As soon as the blowing speed is increased to such an extent that the speed of sound occurs locally on the body, we must expect greater deviations from the incompressible flow.

The so-called critical mach number at which this occurs is equal to 0.40 for the cylinder. Practically a cylinder may be blown with M - 0.30 - 0.35, without special compressibility effects being found. It follows therefore that: in the DVL tunnel the wind speed would have to be increased only by 10 - 20 percent even with greater drag power.

Even in the largest tunnels of the world the Re number could only /1 have been increased by the factor 2 to 5 (by means of the model size). For some of the largest (older) tunnels naturally the turbulence factor is too high to allow reliable investigations related to turbulence phenomena.

Only tunnels of the order of magnitude of the DVL tunnel (and larger), which are also able to blow poorer pressures by several atmospheres in the throat of the tunnel are able to produce much higher Reynolds numbers.

5. Evaluation

The measurements were evaluated on the electronic computer Z23 (manufactured by ZUSE, Bad Hersfeld) of the DVL in Porz-Wahn and plotted with the recording unit Z 64 (Graphomat).

In the evaluation the force of friction of the end discs was subtracted by computer.

To calculate the Reynolds number the air density was taken into consideration as a function of the air pressure and the air temperature.

The tunnel blocking was for the individual cylinders (including that through the lining of the holding shaft):

D /mm/	70	108	156	216	293
(F/F_o)	0.023	0.031	0.043	0.059	0.062

The correction of the blowing dynamic pressure because of tunnel blocking could therefore be disregarded.

6. Discussion of the Measurement Results /11

The drag coefficients measured on the five cylinders are plotted in Diagrams D1 to D9. The survey of the diagrams is given in Table 2.

Diagrams D1 to D5 show the effect of the different surface structures each time for 1 cylinder diameter. In diagrams D6 to D9 the effect of the tube diameter is shown each time for one surface state. It is apparent from the diagrams (in particular D1, D2 and D6 to D9) that the subcritical drag coefficient for Reynolds numbers at the lower limit of the range studied here (up to about Re = 10-5) is independent of the surface state and the cylinder diameter (cW - 1.2).

The critical Reynolds number for the smooth cylinder is independent of the diameter (Diagrams D6 and D10). It is 4.16 by 10-5. This value as will be shown later is an upper limit for the critical Reynolds number.

All other surface states show however a variation of Re-krit with a diameter, a fact which has never yet been studied systematically and which can be considered as totally new.

In Diagram 10 several other individual results of other sources are included for comparison. They fit with our results very well. The following trends exist:

a) Re-krit decreases with increasing ~~unevenness~~ roughness, while apparently according to Diagrams 11 and 12 the "polished" state (D11) has such small individual disturbances that they are no longer effective. But even the small number of defects of 5 to 10 μm height or depth of the surface (b) according to Diagram 12 shows that here the threshold value of the unevenness is exceeded.

b) The Re-krit values for lacquering "with disturbing elements" (dust, impurities) and even more those with "protective paint" ("preservation") and especially those with "point pattern" are noticeably below the values of the smooth surfaces.

c) The practically found values for the unevennesses seem to be clas- /12
sified between the values of a lacquer "with few disturbing elements" and those "with preservation". We can include here surfaces of the type "rough from rolling", "sandblasted" and also those whose paint has suffered from aging.

d) The effect of the cylinder diameter (D10) shows the same tendency for <u>all</u> unevennesses: with increasing diameter the critical Reynolds number will achieve approximately and in an asymptotic manner the critical Reynolds number of the totally smooth surfaces. This is illuminating if we consider the following: in the production of a certain type of surface (a to e) naturally the <u>absolute</u> roughness is <u>independent</u> of the diameter. The <u>relative</u> roughness h/D becomes therefore smaller with increasing diameter. <u>Large</u> cylinders seem aerodynamically more smooth than small ones with the same surface structure, since its roughness elevations are hidden in their thicker boundary layer.

Applied formulae can be derived from these results:

For the <u>supercritical drag coefficient</u> the following may be established:

a) It has the minimum value for smooth polished cylinders ($cW \approx 0.25$).

b) With increasing surface roughness the supercritical cW value increases. In the measurements with point pattern surface it increased for 0.6 for

Re = 1.6 by 10-6 (D9). For the cylinder with smooth surface cW with the same Reynolds number was only 0.48.

c) The supercritical cW values differ both from cylinder to cylinder and from experiment to experiment on the same cylinder. This spread was also established by other authors for example /7/, Fig. 5. It is based not only on the error of the measurement but the flow picture is capable of different states while it may vary from one to the other discontinuously. The spread for smooth polish cylinders is greatest. This is obviously due to the fact that the magnitude of the turbulent wake for the very smooth tubes reacts more sensitively to randomness than for the rougher surfaces.

The measurements carried out by us and others known to us, as we /13 said above are grouped in Diagram D10. In it the critical Reynolds number is plotted against the diameter. The curve parameter is the surface structure. The roundness or lack of roundness of the studied cylinders cannot be eliminated. Only for the measurements carried out here (CIDECT-3) and the measurements published by Delaney and Sorensen /7/ it is certain that exactly circular cylinders were studied. The cylinders used by us in the first experimental section /1/, /2/, /3/, (calibration tube 70 and 108 mm diameter) had rolling defects of $\Delta D/D$ ≤ 0.015. The tubes used in the measurements for the companies Stewarts and Lloyds /6/ were also unmachined rolled tubes. For the single polish tube which is known in /6/, no further details are given. The measurements by Roshko /9/ cannot be included in this diagram, since Roshko carried out measurements only in the supercritical range. He carried out his investigations on rolled and sandblasted tubes, for which he indicates a lack of roundness of $\Delta D/D$ - 0.0035 and a roughness of h = 0.005 mm (h/D = 10--5) /9/. The high Reynolds numbers up to nearly 10-7 were obtained by him because he was able to use an overpressure tunnel (up to 480 m) which however as he himself writes has been demolished since then (his test cylinder was 457 mm in diameter). Unfortunately there are no results by Roshko in the range of critical Reynolds number ("because at low dynamic pressure, the resolution of the pressure measurement system was unreliable and there was not enough time to change this situation") /9, page 348/. Since moreover there are no data on the jet turbulence it seems to be difficult to relate Roshko's measurements with those of other authors. For precisely the measurement results compared with each other in Diagram D10 show that so far few of the parameters considered can have much effect on the measurement results.

Here we should like to indicate that cylinder measurements with high Reynolds numbers (more than 10-6) in wind tunnels are difficult to carry out if no overpressure wind tunnel is available.

In such a tunnel the high Reynolds number is achieved by reducing the kinematic viscosities through high air density. In order to avoid local speed of sound, in the wind tunnel the blowing mach number must not be greater than 0.4. With regard to the speed therefore a limit exists at about 120 m/s (900 kp/m^2 dynamic pressure). (We have measured up to 540 kp/m^2 corresponding to about 93 m/s).

7. Summary /14

The measurements on five cylinders with different surfaces have shown that:

1. The smooth polish cylinder represents an upper limit for the critical Re number. It has the maximum critical Reynolds number: 4.16 by 10-5. The supercritical drag coefficient tends to 0.5.

2. The cylinder with point pattern surface represents the other studied limiting case. The artificial surface roughness causes a reduction of the critical Reynolds number to 2.15 by 10-5. The supercritical drag coefficient tends to 0.6.

3. From the other studied surface structures (b, c and d), whose relative roughness was less than that of the point pattern, the conclusion may be drawn that with increasing surface roughness:
   the critical Reynolds number becomes smaller,
   the minimum drag coefficient (cW-min at Re-krit) becomes larger and the supercritical drag coefficient also increases.

4. With increasing diameter the critical Re number tends to the values for the polished surface.

In our opinion practically a new painted cylinder (tube) should correspond to surfaces a or b. By aging and erosion however the relative roughness increases in time. The case of an artificially aged paint (by sandblasting) could not be implemented with our means. The case e may hardly occur practically. These would happen if the steel structures were exposed to very unfavorable conditions and remained without maintenance over a period of years.

REFERENCES

1. Schulz, G. and F. Hayn, Drag Measurement in Tubular Structural Elements Part I: Tubes and Flat Tube Joints. Report 1-NK-I-66-19 (AM 506) of the Institute of Gas Dynamics of the Jeuna Aeronautics and Space Test Center (1956). /15

2. Schulz, G. and F. Hayn: Drag Measurements on Tubular Structure Elements Part I: Tubes and Two-Dimensional Joints. Report 1-NK-I-66-20 (AM 506) of the Institute of Gas Dynamics of the Jeuna Aeronautics and Space Test Center (1966).

3. Schulz, G. and F. Hayn: same as /1/.

4. Hayn, F., Drag Measurements in Tubular Structural Elements Part II: Three-Dimensional Mast Section and Mast Section Plane. Translation of above report /4/ by CIDECT (1967).

5. Hayn, F. Drag Measurements on Tubular Structure Elements Part II: Three-dimensional and Plane Mast Sections - Übersetzung des vorgenannten Berichtes /4/ durch CIDECT (1967).

6. Aerodynamic Drag and Shielding - Stewarts and Lloyds Ltd., Department of Research and Technical Development, Corby: Report No. E 56/22.

7. Delaney, Noel K. and Norman E. Sorensen, Low Speed Drag of Cylinders of Various Shapes - NACA TN 3038 (1953).

8. Fage, A. and V.M. Falkner, Further Experiments on the Flow Around a Circular Cylinder - ARC R&M No. 1369 (1931).

9. Roshko, A., Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number - J. Fluid Mechanics 10, 1961, p. 345-356.

Meß-abschn.[1]	Modell[2]	End-scheibe[3] D/d	Staudruck[4] [kp/m²]	Re-Zahl[5]	Oberflächen[6]
1	Rohr[7] 70 mm ⌀	4	10 ... 520	$0{,}5 \cdot 10^5 \ldots 4{,}5 \cdot 10^5$	(a) glatt gedreht und poliert[8] (b) Lack mit wenig Störkörpern (c) Lack mit viel Störkörpern (d) Konservierung (e) glatt mit Punktmuster
2	Rohr 100 mm ⌀	4	10 ... 520	$0{,}8 \cdot 10^5 \ldots 6 \cdot 10^5$	
3	Rohr 156 mm ⌀	4	10 ... 520	$1{,}2 \cdot 10^5 \ldots 1 \cdot 10^6$	
4	Rohr 216 mm ⌀	4	10 ... 520	$1{,}7 \cdot 10^5 \ldots 1{,}3 \cdot 10^6$	
5	Rohr 293 mm ⌀	4	10 ... 520	$2{,}3 \cdot 10^5 \ldots 1{,}6 \cdot 10^6$	

Key: 1. measurement section; 2. model; 3. end disc; 4. pressure head; 5. Re number; 6. surfaces; 7. tube; a. smooth turned and polished; b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. smooth with point pattern.

Table 1: Measurement Program (Review)

Diagr. Nr.[1]		Benennung[2]	Parameter[11]
1	Cyl (Re)	Zylinder[3]: 70mm$^{\phi}$	Oberflächen[12] (a, b, c, d)
2		-"- : 108mm$^{\phi}$	
3		-"- : 156mm$^{\phi}$	
4		-"- : 216mm$^{\phi}$	
5		-"- : 293mm$^{\phi}$	
6		Zylinderoberfläche[4]: glatt (gedreht u. poliert)	Rohr-durchmesser[13]
7		-"- [5]: Lack m. wenig Störkörpern	
8		-"- [6]: Lack m. viel Störkörpern	
9		-"- [7]: glatt mit Punktmuster	
10	Re_{krit} (D)	Krit. Reynoldszahl v. Zylindern m. versch. Durchm. u. versch. Oberfläche[8]	Oberflächen[12]
11	$\frac{n}{N}$ (h)	Rauhigkeitsverteilung an glatten[9] (gedrehten u. polierten) Zylindern	Rohr-durchmesser[13]
12		Rauhigkeitsverteilung an gestrichenen[10] Zylindern (Lack ohne Störkörper)	

Key: 1. diagram number; 2. designation; 3. cylinder; 4. cylinder surface: smooth (turned and polished); 5. lacquer with few disturbing elements; 6. lacquer with many disturbing elements; 7. smooth with point pattern 8. critical Reynolds number of cylinders with different diameter and different surface; 9. roughness distribution on smooth (turned and polished) cylinders; 10. roughness distribution on painted cylinders (lacquered without disturbing elements); 11. parameters; 12. surfaces; 13. tube diameter.

TABLE 2

Diagram - Review

D [mm]	70	108	156	216	293	Mittelwert[1]
h [µm]			100 · n/N [%]			
-12					0	0
-11			0	0	1	0,2
-10			1	1	0	0,4
- 9	0	0	0	0	0	0
- 8	2	1	1	1	0	1
- 7	0	2	0	1	0	0,6
- 6	0	0	2	1	0	0,6
- 5	0	1	1	0	1	0,6
- 4	5	1	1	2	0	1,8
- 3	6	1	1	0	3	2,2
- 2	0	1	0	5	1	1,4
- 1	22	11	6	9	20	13,6
0	42	41	49	56	46	46,8
1	16	30	30	19	22	23,4
2	5	5	2	2	2	3,2
3	1	1	3	0	0	1,0
4	1	3	1	1	1	1,4
5	0	0	1	1	1	0,6
6	0	0	0	1	1	0,4
7	0	0	0	0	0	0
8		0	0			0
9		0	0			0
10		2	1			0,6
11		0	0			0
12						0

D = Zylinder-Durchmesser [mm]

h = gemessene Rauhigkeitserhebung, ("Störungen") [µm]

n = Zahl der Störungen einer bestimmten Höhe h.

N = Summe der Störungen <u>aller</u> vorkommenden Höhen,

<u>positiv</u> = Korn, Fleck, Muster

<u>negativ</u> = Riefe, Rille, Kratzer, Eindruck

Key: 1. average; D = cylinder diameter (mm); h = measured roughness elevation ("disturbances") (µm); n - number of disturbances of a certain height h; N = sum of disturbances of <u>all</u> occurring heights; <u>positive</u> = grain, spot, pattern; <u>negative</u> = ridge, groove, scratch, imprint.

Table 3: Roughness distribution for surfaces (a): smooth, turned and polished.

D [mm]	70	108	156	216	293	Mittelw.	D	70	108	156	216	293	Mittelw.
h [µm]	100·n/N [%]						h	100·n/N [%]					
										1(28)	1(32)		
-25					1		25				1	1	0,4
-24							24				0	0	0
-23							23				1	0	0,2
-22							22				0	0	0
-21				1			21				0	0	0
-20				0	3		20			1	1	0	0,4
-19				0	0		19			0	0	0	0
-18			0	0	1	0,2	18			0	0	1	0,2
-17			1	2	0	0,6	17			0	1	0	0,2
-16			1	0	0	0,2	16			1	1	0	0,4
-15			0	0	1	0,2	15			2	3	1	1,2
-14			0	0	1	0;2	14			0	0	0	0
-13		0	2	1	1	0,8	13			1	0	0	0,2
-12		1	1	2	1	1,0	12			1	1	0	0,4
-11		0	1	0	2	0,6	11			1	0	0	0,2
-10		0	2	5	0	1,4	10		1	3	1	5	2,0
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- 7		0	0	0	1	0,2	7	1	0	3	2	2	1,6
- 6		0	0	2	2	0,8	6	0	0	4	0	3	1,4
- 5	0	0	4	5	5	2,8	5	0	1	5	3	4	2,6
- 4	1	2	0	4	0	1,4	4	0	2	0	4	6	2,4
- 3	1	0	0	0	2	0,6	3	1	1	1	2	1	1,2
- 2	4	5	2	5	1	3,4	2	3	1	1	8	3	3,2
- 1	36	29	3	7	15	18,0	1	14	24	1	2	10	10,2
0	39	32	52	28	27	35,6							

D = Zylinder-Durchmesser [mm]

h = gemessene Rauhigkeitserhebung, ("Störungen") [µm]

n = Zahl der Störungen einer bestimmten Höhe h.

N = Summe der Störungen <u>aller</u> vorkommenden Höhen.

<u>positiv</u> = Korn, Fleck, Muster

<u>negativ</u> = Riefe, Rille, Kratzer, Eindruck

Table 4: Roughness distribution for surface (b): lacquer with few disturbing elements. Key: 1. average; D = cylinder diameter (mm); h = measured roughness elevation ("disturbances") (m); n = number of disturbances of a certain height h; N = sum of disturbances of all occurring heights; positive = grain, spot, pattern; negative = ridge, groove, scratch, imprint.

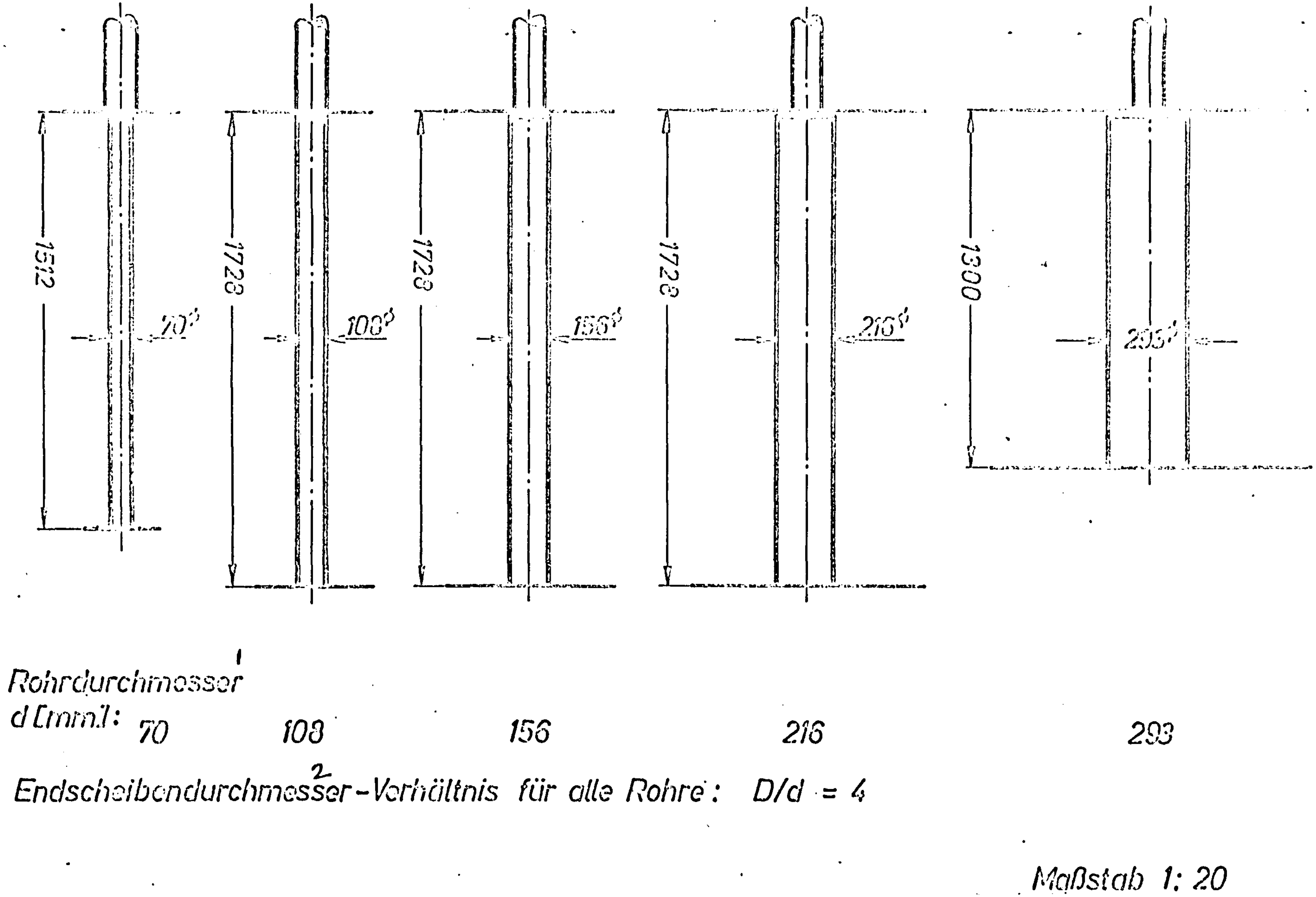


Figure 1: Model Dimensions Key: 1. tube diameter; 2. end disc diameter ratios for all tubes.

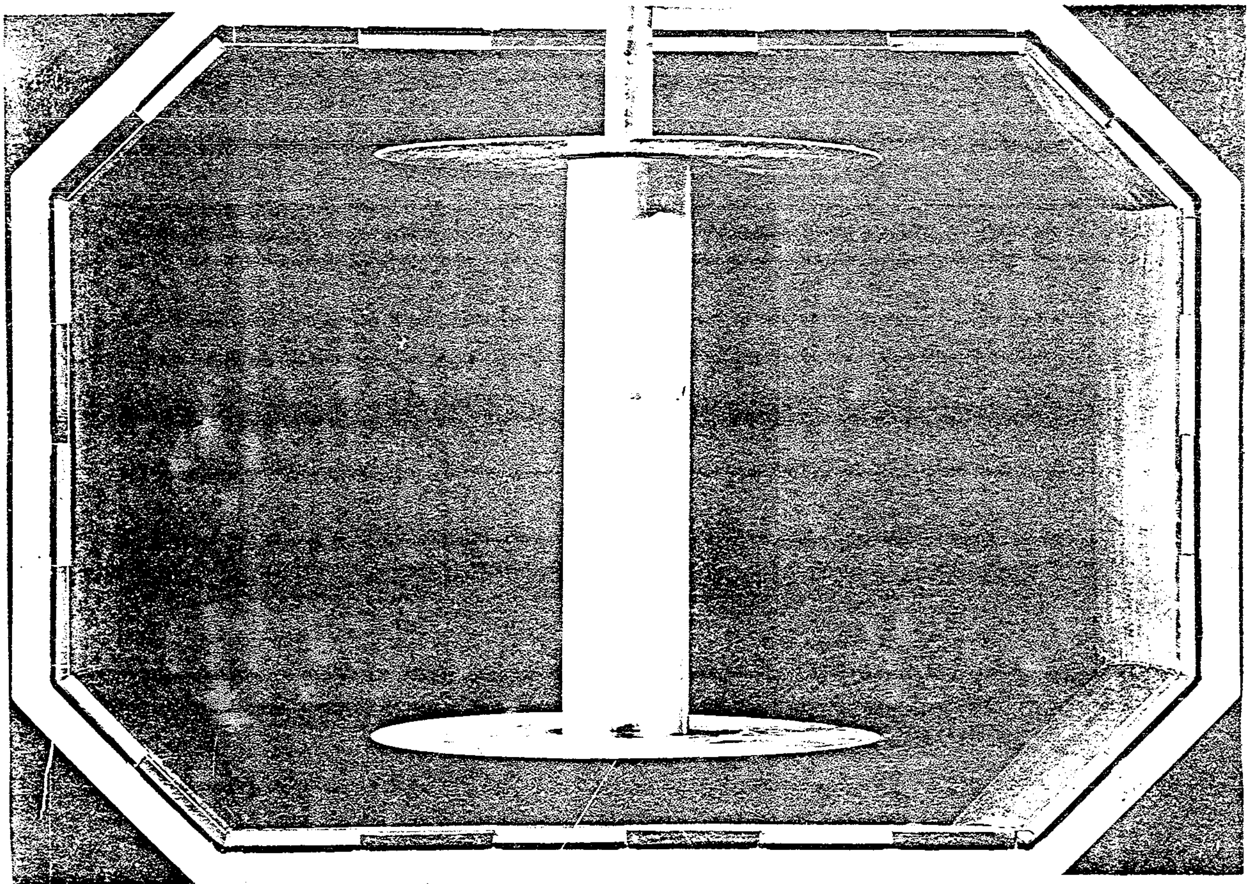


Figure 2: Cylinder 293 mm diameter with polished surface in the tunnel throat.

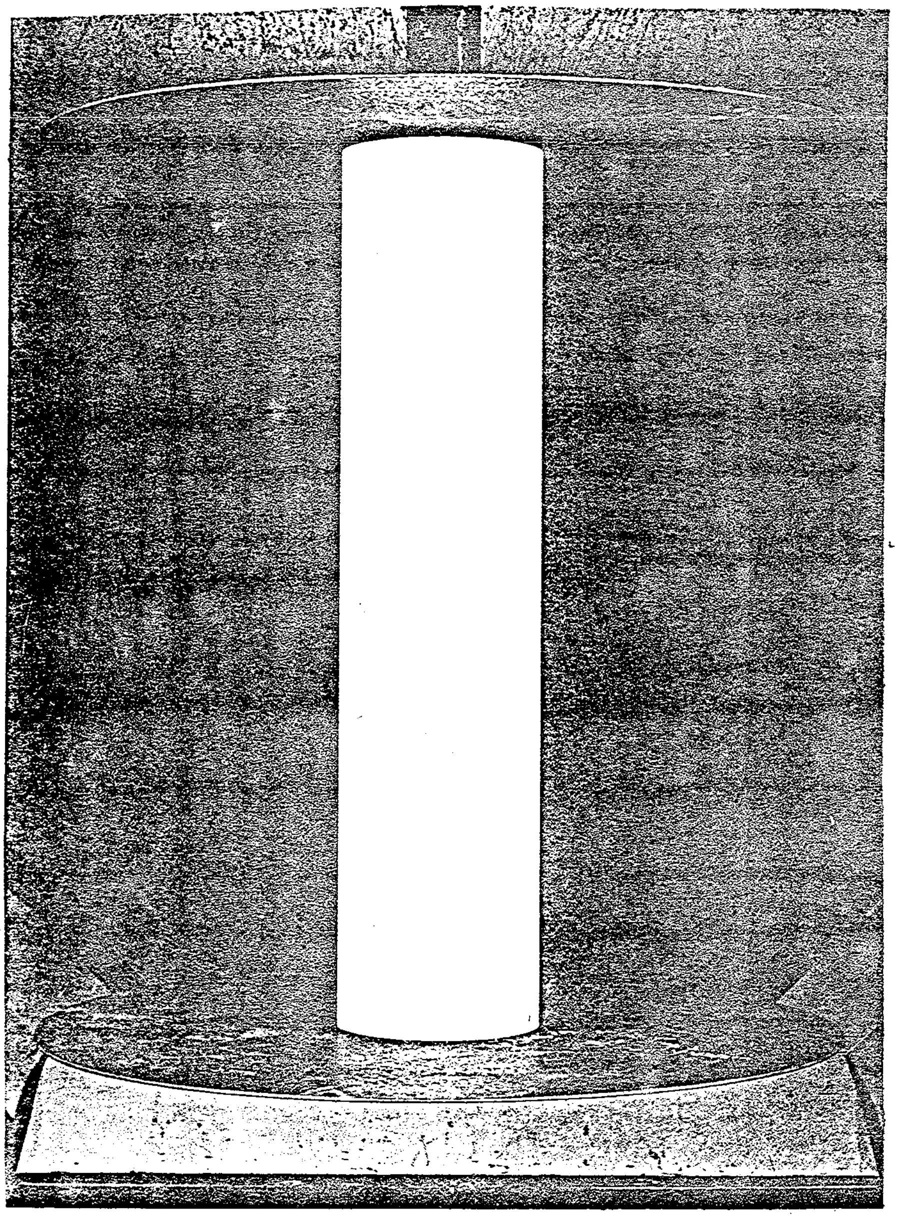


Figure 3: Cylinder 216 mm diameter with point pattern in the tunnel throat.

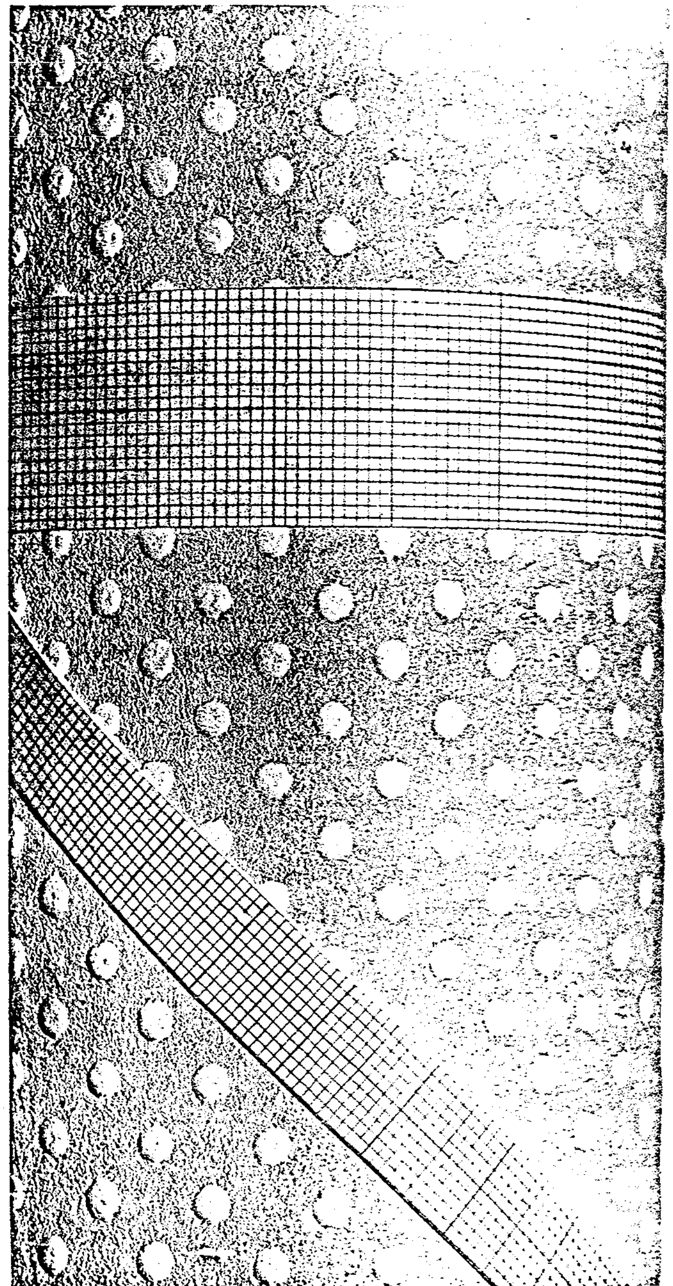


Figure 4: Point pattern photo of a cylinder of 108 millimeters diameter.

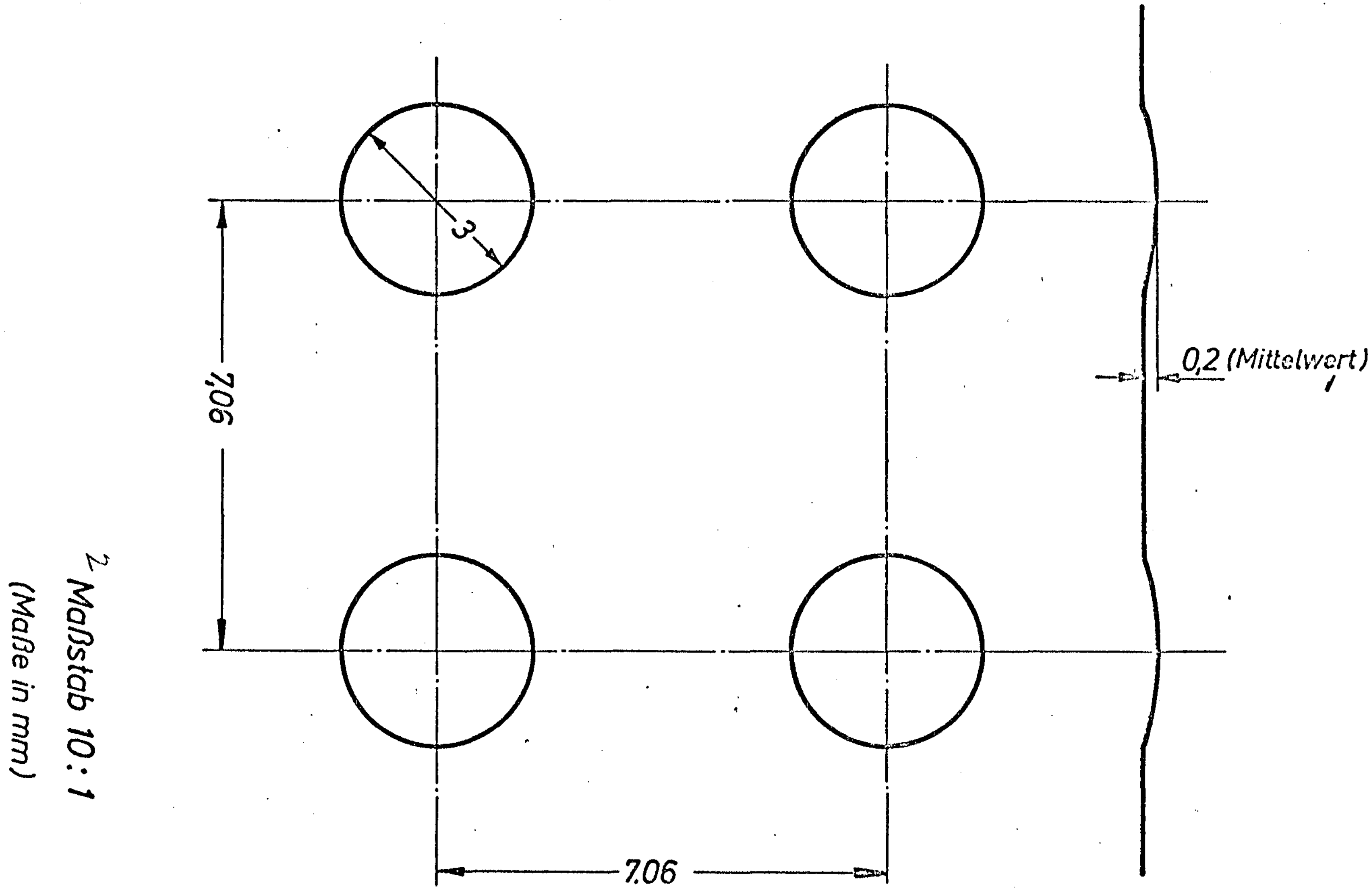


Figure 5: Measurement of the point patterns. Key: 1. average 2. scale
(dimensions in mm)

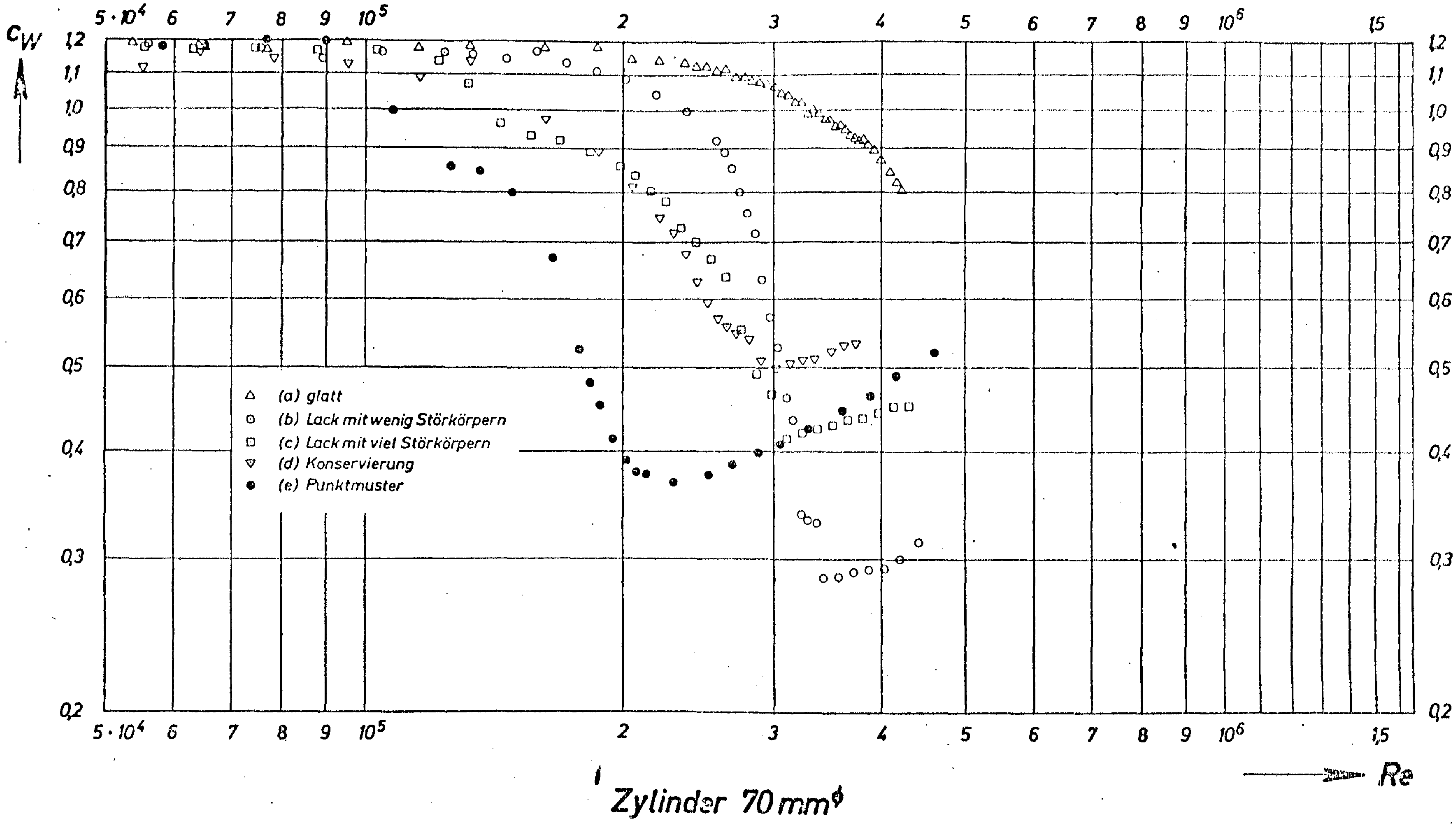


Diagram 1: Cylinder 70 mm diameter - Surface variation. Key: a. smooth b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. point pattern; l. cylinder.

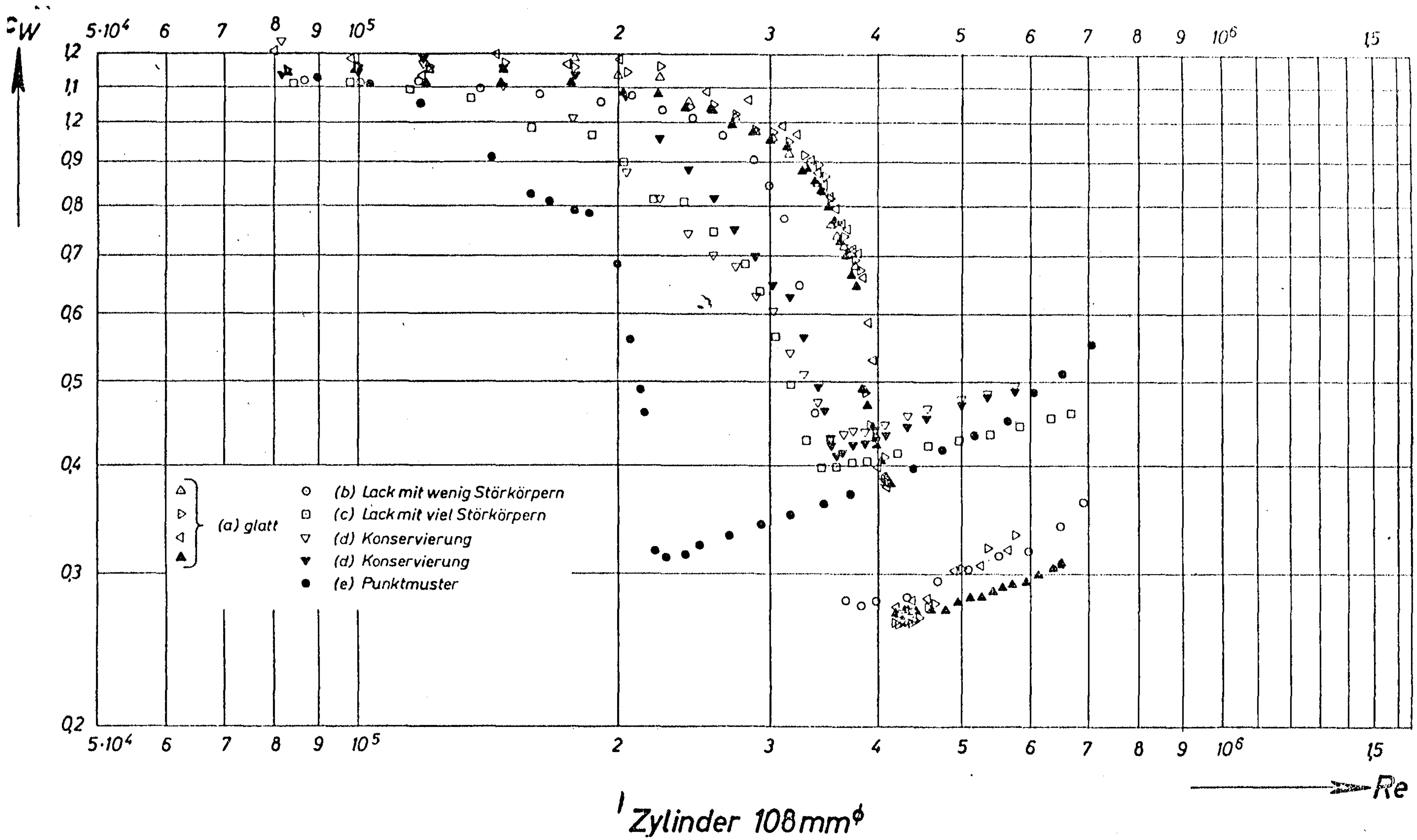


Diagram 2: Cylinder 108 diameter - Surface variation; Key: 1. cylinder; a. smooth; b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. point pattern

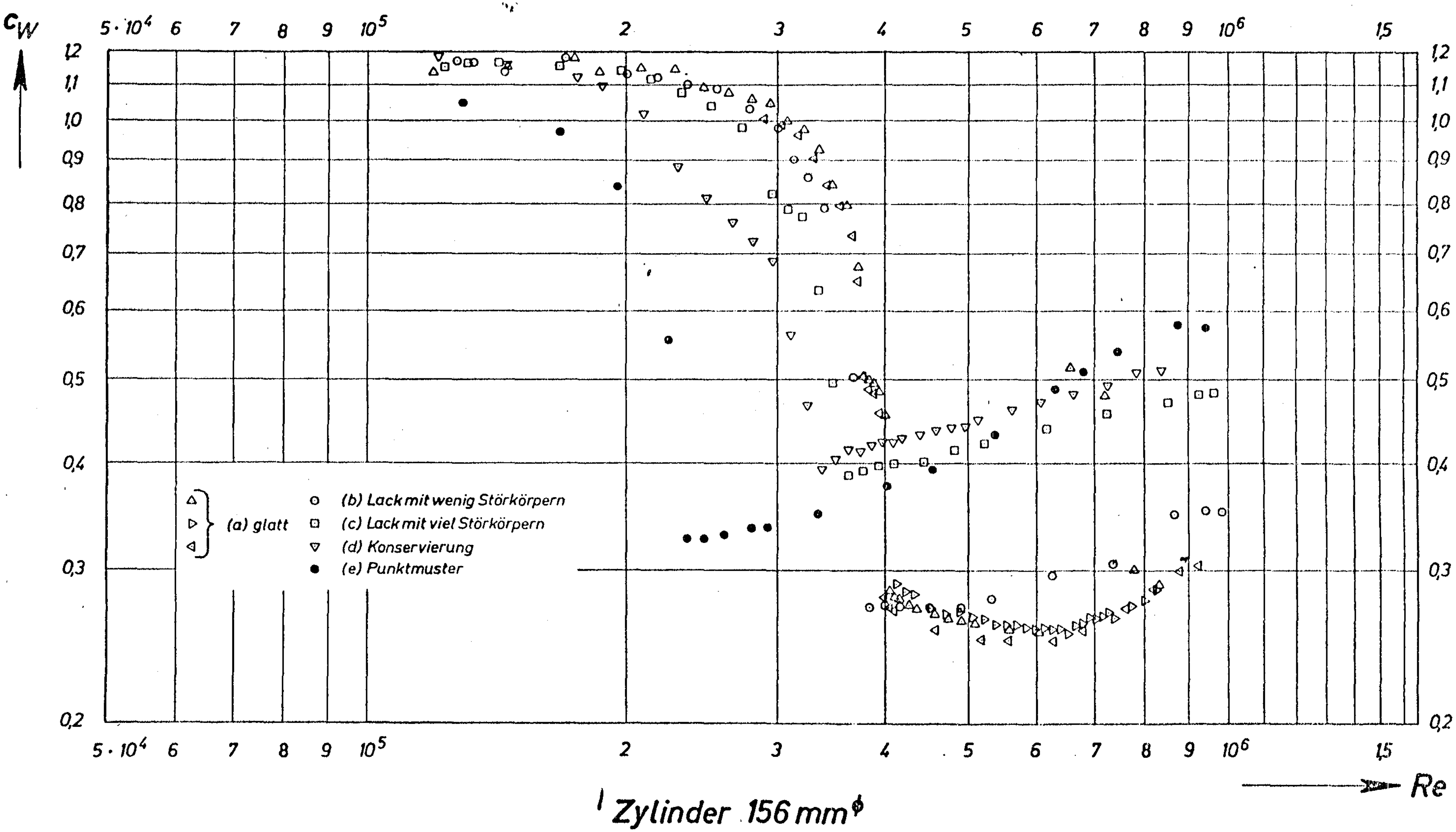


Diagram 3: Cylinder of 156 diameter - surface variation; Key: 1. cylinder; a. smooth; b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. point pattern.

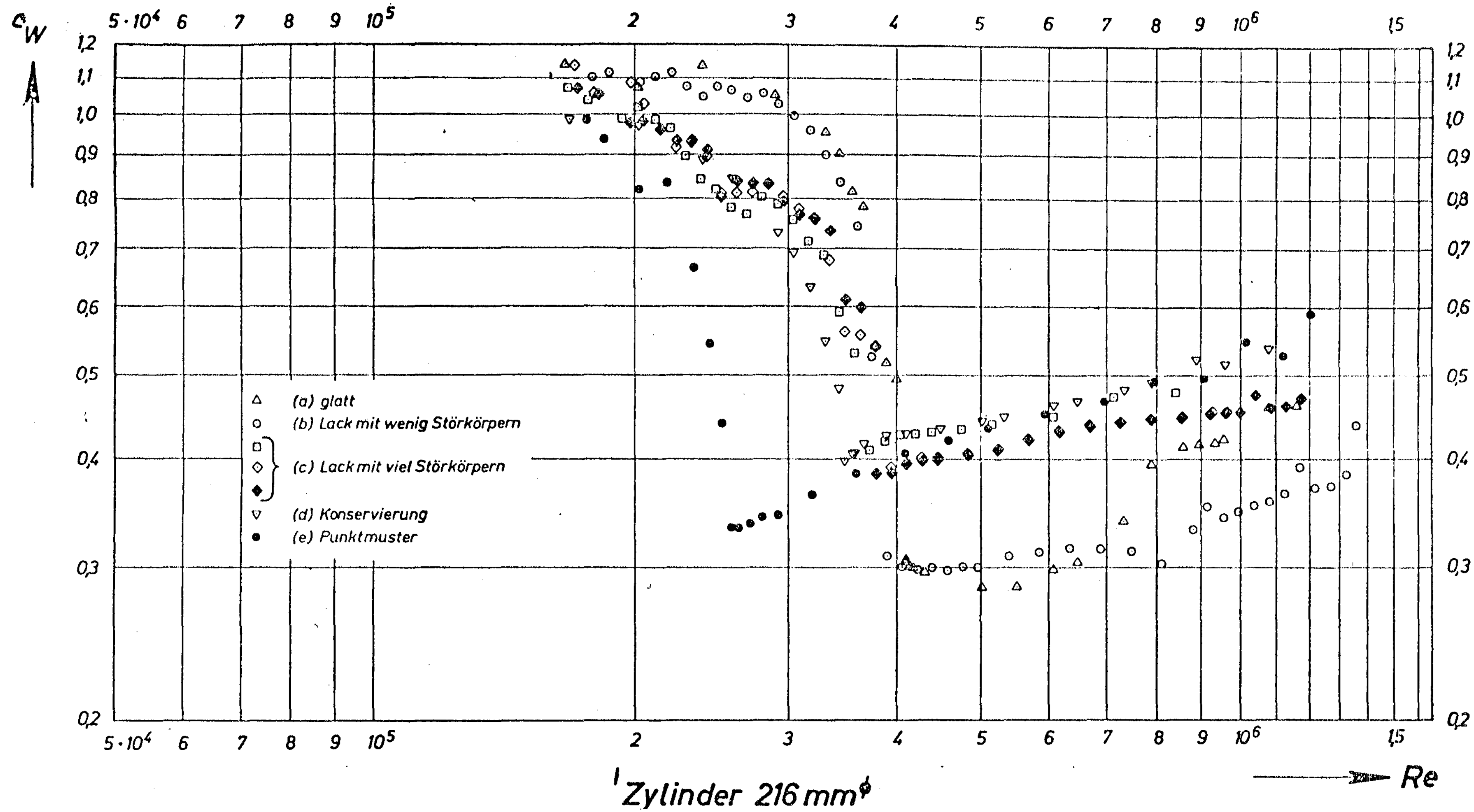


Diagram 4: Cylinder of 216 diameter - surface variation; Key: 1. cylinder; a. smooth; b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. point pattern.

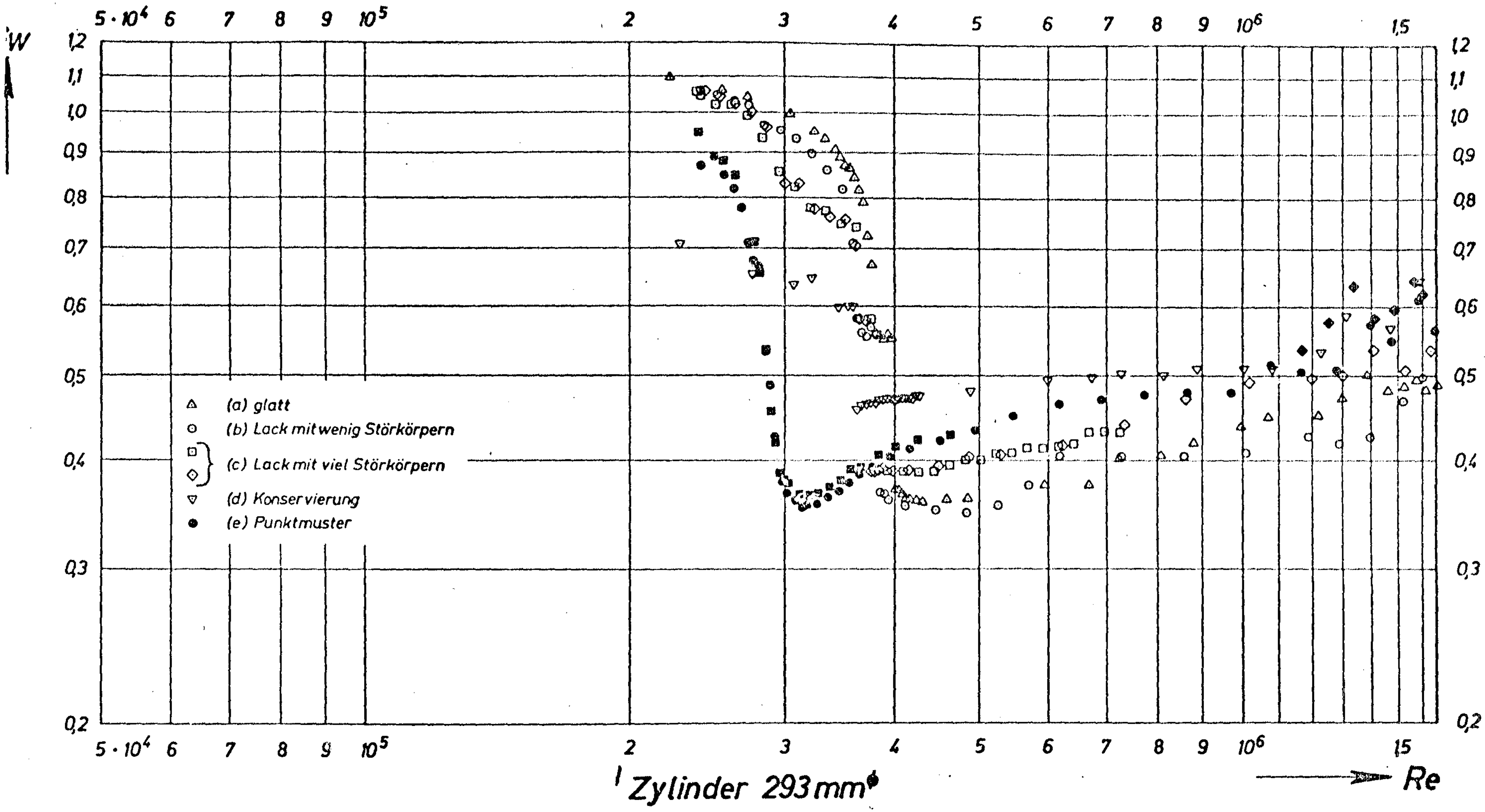


Diagram 5: Cylinder 293 diameter - surface variation; Key: 1. cylinder; a. smooth; b. lacquer with few disturbing elements; c. lacquer with many disturbing elements; d. preservation; e. point pattern.

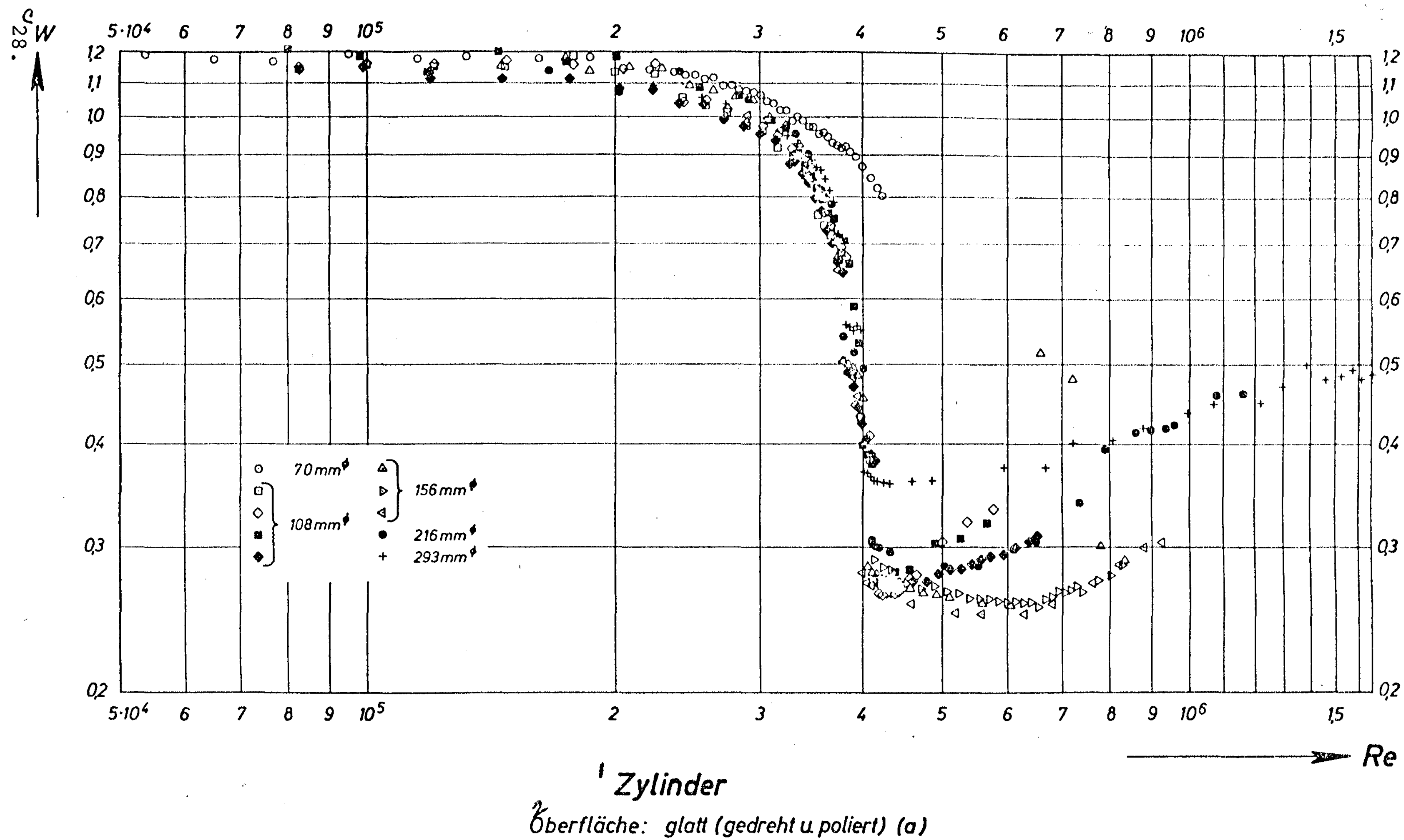


Diagram 6: Cylinder surface: smooth, turned and polished; Key: 1. cylinder; 2. surface: smooth (turned and polished) a.

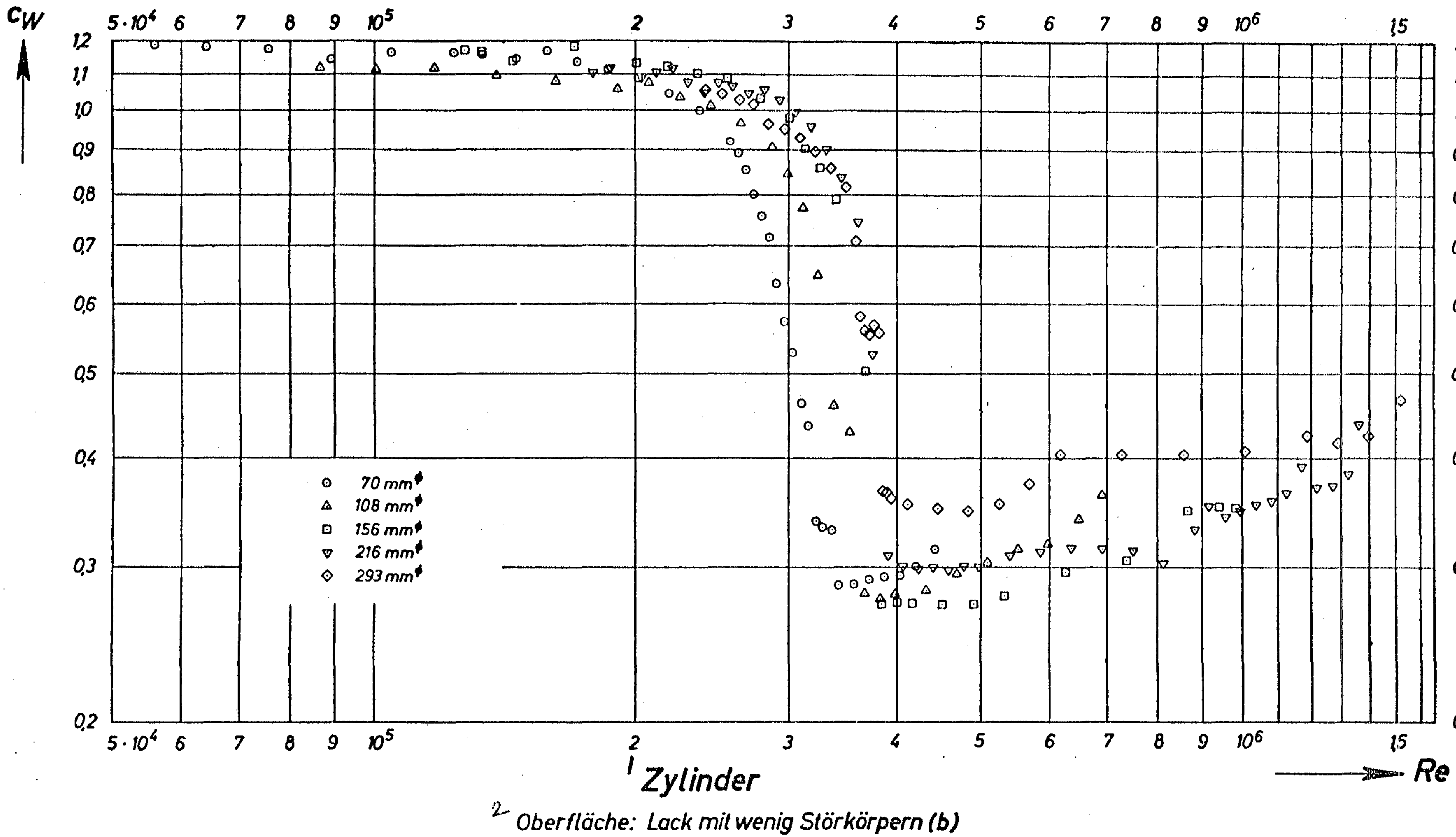
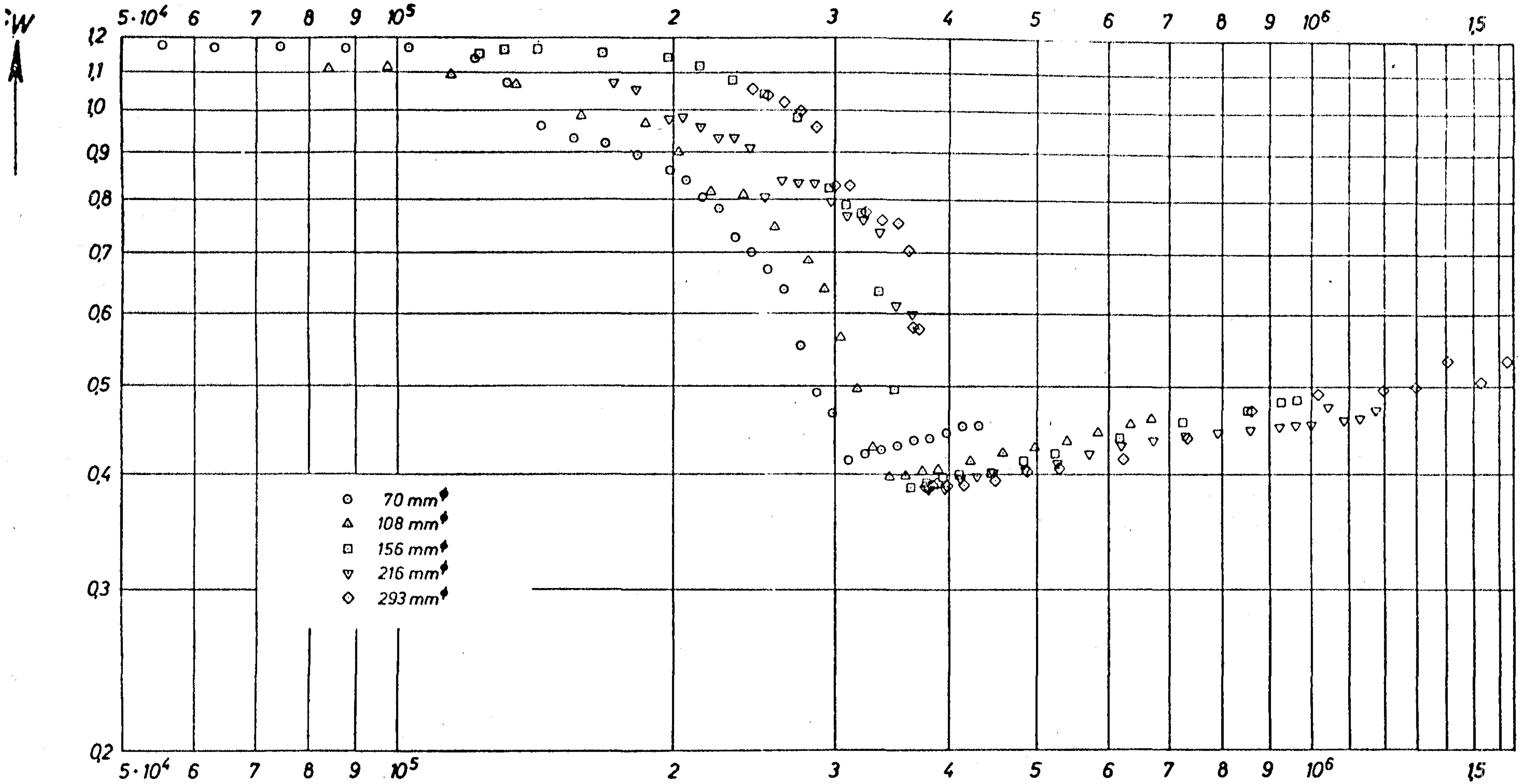


Diagram 7: Cylinder surface: lacquer with few disturbing elements;
Key: 1. cylinder; 2. surface: with few disturbing elements (b).



1 Zylinder

2 Oberfläche: Lack mit viel Störkörpern (c)

Diagram 8: Cylindrical surface: lacquer with many disturbing elements.
Key: 1. cylinder; 2. surface lacquers with many disturbing elements (c).

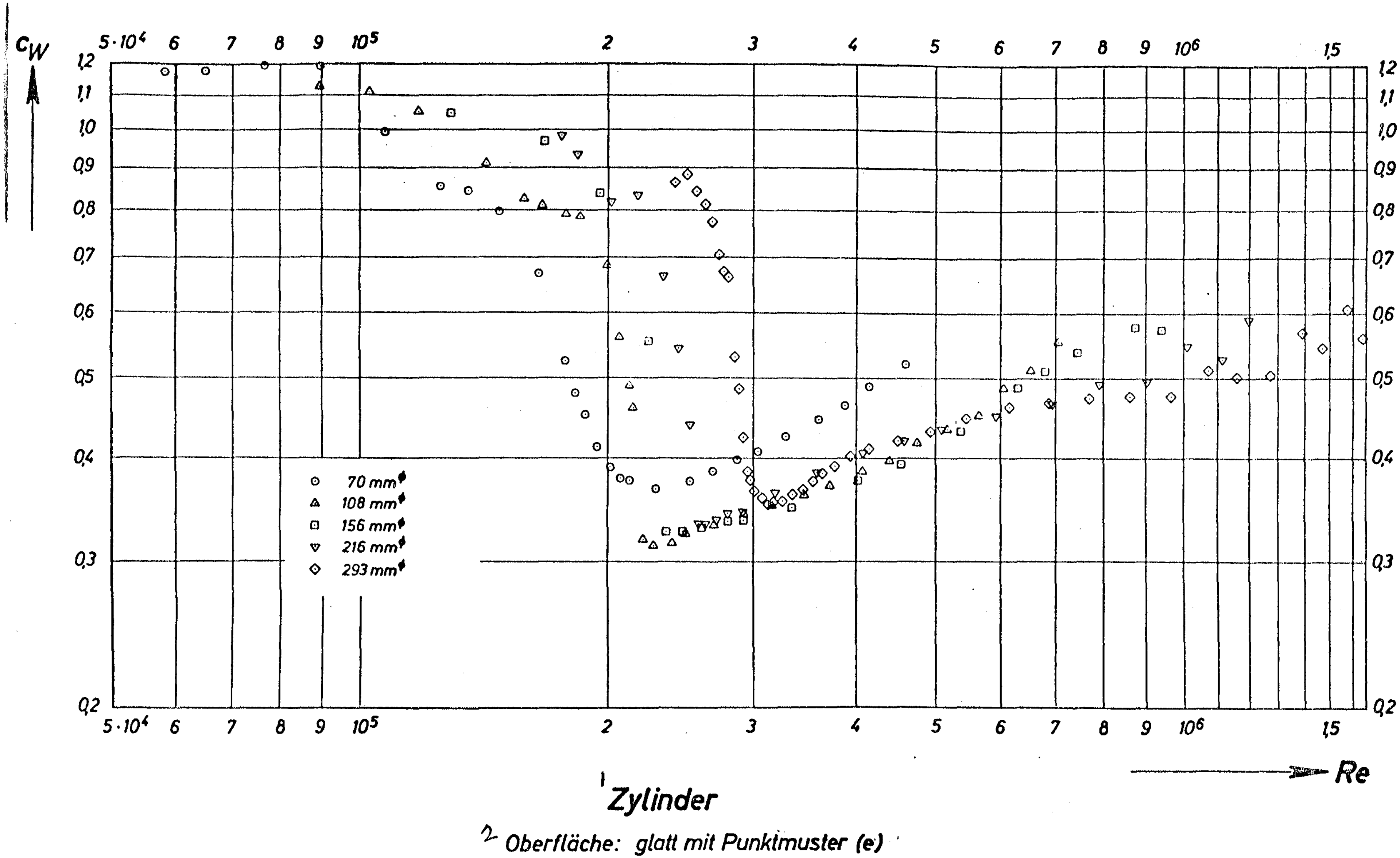
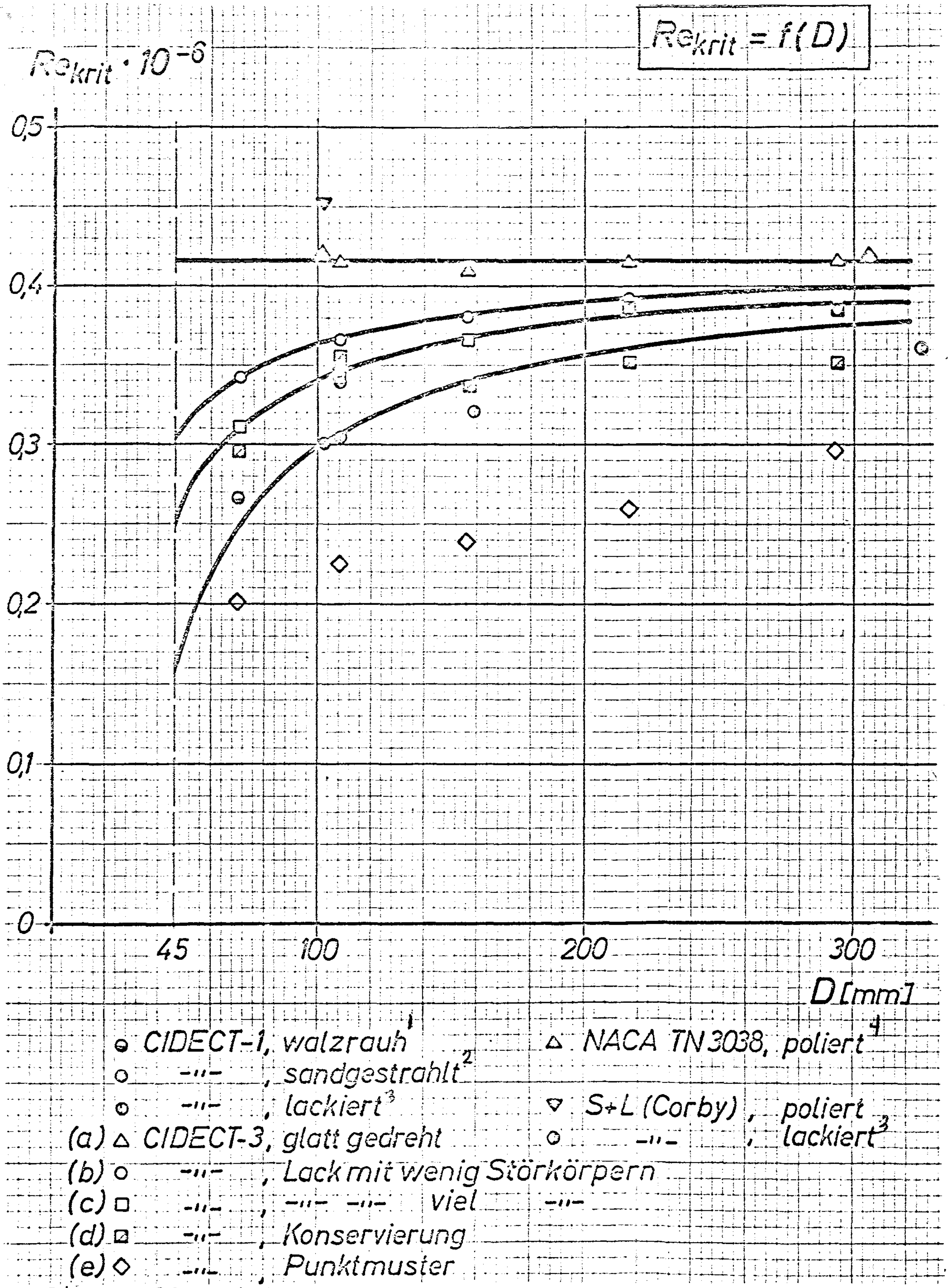


Diagram 9: Cylinder surface: smooth with point pattern. Key: 1. cylinder; 2. surface: smooth with point pattern (e).



32. Diagram 10: Critical Reynolds number of cylinders with different diameter and different surface: Key: 1. rough from rolling; 2. sand-blasting; 3. lacquered; 4. polished; a. smooth turned; b. lacquer with few disturbing elements; c. lacquer with many disturbing element d. preservation; e. point pattern.

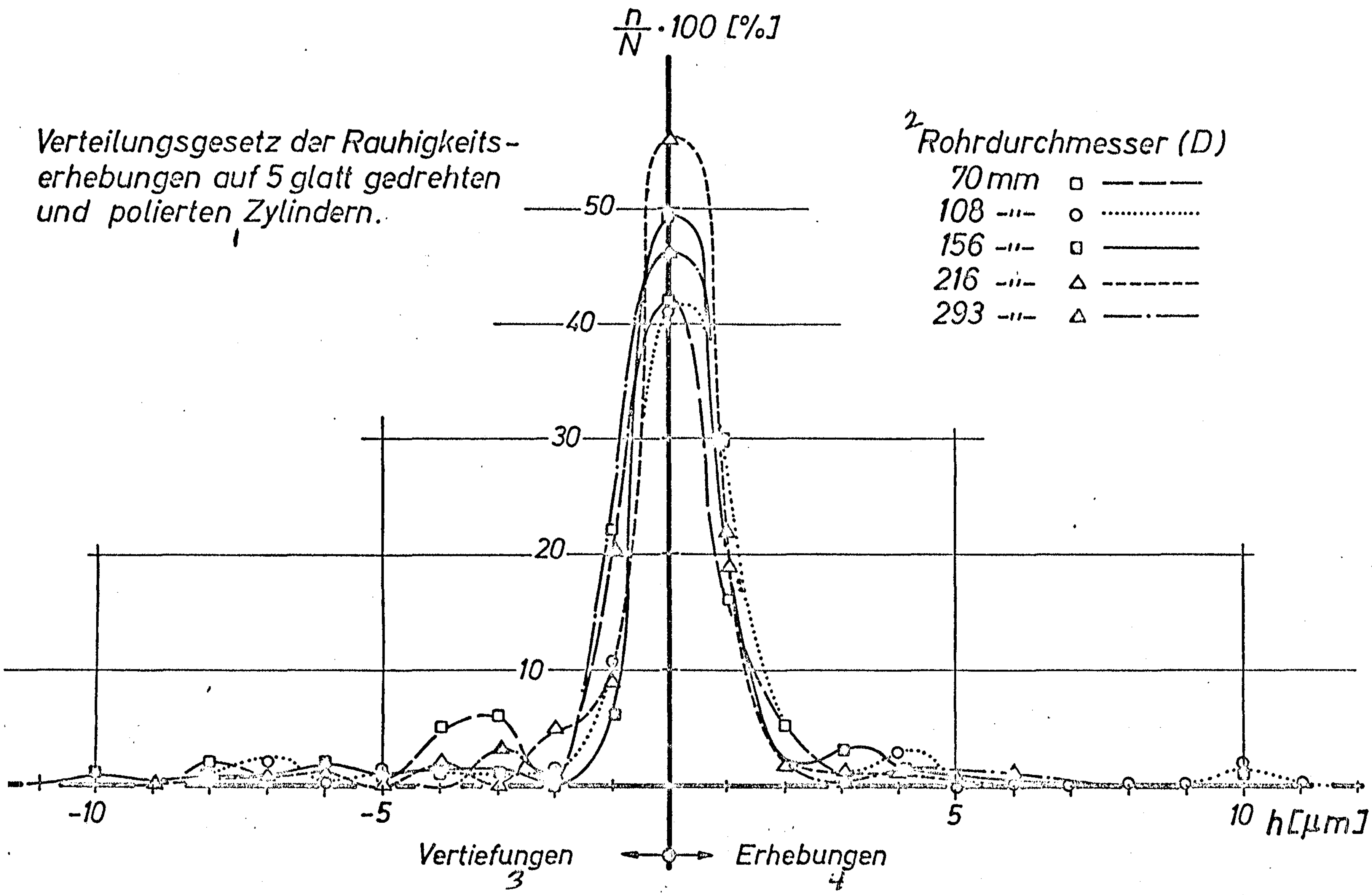


Diagram 11: Roughness distribution for smooth turned and polished surface (a).
Key: 1. distribution law of roughness elevations on five smooth turned and polished cylinders; 2. tube diameters; 3. depressions; 4. elevations.

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