THE GEOMETRICAL STATE OF THE SURFACE OF A SOLID

by Prof. Dr.-Ing. H. von Weingraber
Brunswick, Germany

1. INTRODUCTION

The functional performance of two surfaces in contact depends upon their material properties as well as their geometrical properties. The physical and chemical properties that a surface acquires during machining can be very different from those of the underlying undisturbed material. They are just as important for a complete typological description as the geometrical state, but their discussion is beyond the scope of this paper. The following discussion is, therefore, restricted to those problems which are related to an unambiguous characterization of the geometrical state.

2. THE REQUIREMENTS OF A GEOMETRICAL DESCRIPTION OF THE SURFACE

If an engineer were to set himself the task of describing geometrical surfaces in an unambiguous manner (establishing clear definitions, specifications, and standards for practical purposes) he would have to begin with the following considerations:

Considered either as a whole or in section, a fabricated surface will never completely conform to the specified ideal geometry. The resulting imperfections or deviations will depend on the manufacturing process. The fundamental question is "What is the most suitable means of determining the deviation from the specified geometry?" Figure 1 shows a concise, unified organization of measurements, that leads to the most suitable methods in a logical way. In practice, the imperfections of a surface are measured from one or more profile-sections. By this method, however, the only imperfections revealed are those of the particular cross-sections. It is questionable whether or not the largest and most dangerous imperfections are determined. A three-dimensional measurement of surface imperfections would be a great step forward. Therefore, a distinction is drawn in Step I between measurements made from profiles and three-dimensional measurements. This distinction will be important to later development of definitions.

Because the type and size of imperfections can influence the behavior of a surface in widely differing ways, they must be organized in a useful manner (Step II). Inevitably, the first requirement is for definitions that describe the different orders (classes) qualitatively and provide some means of distinguishing between them. This is especially difficult if the definitions are to apply equally well to two-dimensional (profile) measurements and three-dimensional measurements.

Only after such definitions have been established can we progress to Step III with any hope of success. In this step the different orders (classes) are described, by appropriate parameters, in both the horizontal and vertical directions. Again, this is not possible without precise definitions.

After establishment of the most suitable parameters, the problem of how to measure them (Step IV) can be attacked. Instruments must be developed that produce numerical values that are accurately related to the definitions. All of the foregoing steps must be satisfactorily carried out before a useful characterization of the desired surface finish (Step V) can be given to the designer for use in drawing and other manufacturing specifications.

3. THE PRESENT, UNSATISFACTORY STATE OF THE ART, ILLUSTRATED BY EXAMPLES

The definitions, specifications, and standards presently in use in the field of surface geometry are not the result of a logical consideration of real needs, such as those outlined in Section 2. Rather, they are an accumulation of definitions and procedures that were developed somewhat arbitrarily to satisfy specific rather than general problems, and lack a basis in causality and intrinsic logic. This state of confusion has many origins. For example, measurements of surface roughness were made before it had been determined what was to be considered roughness. There was a definite preference to choose, from the many measurement methods that were developed, those that produced numbers in the most elegant way. The numbers that were produced varied widely, depending on the type of measuring process that was used. Practical experience has shown that the various practices used in different countries have serious deficiencies, but because of the natural resistance to change, they continue in use. Despite these deficiencies, millions of drawings have been produced using these practices. Therefore, it is understandable that one finds such resistance to change. Attempts to decrease the deficiencies through various compromises in the different countries have resulted in still greater confusion. Science and industry find this situation equally untenable because it makes cooperation and communication extraordinarily difficult. The correction of this situation is just as important as it is difficult.

There is not space in this paper to take up all of the complex problems that exist. We must, therefore, be content to illustrate some special problem areas by means of examples that are arranged according to the five points outlined previously.

Step I: The inspection of a workpiece surface cannot be limited to a single small section. The surface must inevitably be considered as a whole. Therefore, it is not correct to limit measurements to a single profile as is now common practice. There should be an attempt to describe the surface three-dimensionally or integrally as explained in the following:

A simple case of two surfaces interacting is a shaft in a bore: A clearance exists (Fig. 2) if the diameter D_s of the largest right circular cylinder inscribed within the bore B is greater than the diameter d_s of the smallest right circular cylinder that circumscribes the shaft W. In the extreme case the two right circular cylinders, which in Germany are called "Stutzzylinder" (adjacent cylinders), have the same diameter, $D_s = d_s$; the so-called mating size (clearance = 0).

One can measure the diameters D_x, D_y and d_x, d_y of the bore and the shaft respectively at various planes XX', YY' or measure their roundness and their straightness or concentricity, but none of these measurements establish with any certainty whether or not sufficient clearance exists. The only sure criteria for the existence of clearance are the diameters of the inscribed (D_s) and circumscribed (d_s) cylinders which can only be found from three-dimensional measurements. But the means for making these measurements has, as yet, not been developed. Achievement of a unique, three-dimensional description of bores and shafts is a related problem. It is obvious that the imperfect components W and B theoretically have no true axis or diameter. These are determined from the circumscribed and inscribed cylinders with the diameters d_s and D_s and the axes aa' and AA', respectively.

Step II: Until now, the geometrical errors of surfaces (form error, waviness, and roughness) have not been systematically classified or defined. Widely divergent conceptions of these terms have resulted in misunderstandings and differing measurement results. In this, the problems of three-dimensional as well as two-dimensional definitions are to be considered. The following example illustrates just how confused the situation is, with respect to efforts to obtain a uniform geometrical description of surfaces, and outlines some possible means if improvement:

Figure 3a shows an axial cross section of a cylindrical surface of length L. As this is not truly a cylindrical surface, it theoretically has no axis and, therefore, it can only approximately be adjusted with respect to a reference surface, e.g., a plane. The form deviations, which are obviously much greater than the superposed roughness, are usually found by means of an indicator with a stylus having a radius r_f. The recorder trace would be the path p_f, which is identical to the German standard form profile. The line p_f is the line in the two-dimensional system from which the form deviations (errors of form of the first order (class)) have been measured. In this example the German definition of form deviation is the deviation of p_f from the generatrix p_s of the circumscribing right circular cylinder (Stutzzprofile). This definition conforms to German standard DIN 7182, paper 4 (1). Form deviations are defined therein as "those deviations of the form surface of the workpiece from the nominal geometrical shape, or in the special case of profile sections, as the deviation of the form profile from the nominal geometrical profile." The form surface, as uniquely defined in the DIN 4762, paper 3 (2), is the shape of the body determined by a tracer, with the radius r_f, tracing point-to-point over the total surface. It thus is an attempt to define the errors of form three-dimensionally and not by means of profile sections. The form surface provides a unique boundary between form errors and the other components of the total surface geometry. A similar precise definition is not to be found in the corresponding ISO-draft (3). To get that part of the surface geometry called roughness, a tracing instrument which has a stylus with a radius of curvature of a few microns is used. Waviness is filtered out by means of an electrical filter. Consequently, roughness is determined from the straightened profile plot p_i', i.e., as if the wavy profile p_i did not exist. By these methods both the form deviations and the roughness are determined without consideration of the existing waviness. There is general agreement on the actual existence of such waves. However, the interpretation of the word "waviness" varies widely. Some of the existing versions are as follows:

1. Electrically defined waviness is the long wavelengths of a Fourier series description of the surface that are not passed by the roughness filter (see B. S. 1134: 1961 (4) and ASA B 46.1 - 1962 (5));

2. Those geometrical deviations considered as waves, for which the ratio, depth divided by distance, exceeds a certain maximum;

3. In accordance with the concepts of Fig. 2, the German standard DIN 4762, paper 3 (2) defines waviness (shape deviations of the 2nd order (class)) for the first time as that part of the geometrical deviations that lies between the form profile p_f and the envelope profile p_e, which is explained later in this paper.

   For the measurement of waviness, a shorter reference length l_w, say, three wavelengths, is sufficient. In Fig. 3b, for clarity, the length l_w has been made equal to L. The arcs of the form profile p_f, which are more flattened in Fig. 3b, are the logical and unique boundary between waviness and form error. In the German standard, the boundary between waviness and roughness is taken to be the profile p_e, which is formed in the same way in which p_f is formed. The difference is that instead of a stylus of radius r_f being used, a stylus with a radius r_e, smaller than r_f, is used. Waviness is defined as the deviation between the curves p_e and p_f over the reference length l_w.

The three definitions of waviness, 1, 2, and 3, cannot be made to agree. According to the definitions used, the measurements will be different and the results will not be comparable. Here lies the basis for the principal misunderstandings and for the discussions, which have so far remained fruitless.

Only the German definition for waviness, given in Part 3 (for clarity, it is better to call them shape deviations of the 2nd order (class)) is satisfactory and unique. Correspondingly exact definitions for waviness do not exist in the other national standards. In contrast, there are a large number of more or less divergent national definitions for roughness in the various national standards. In Germany, roughness is also called shape deviations of the 3rd to the 5th order (class). The oldest of these are based on an averaging line m (M-system), Fig. 3c, called either a mean line or a center line (see (4)). The sampling length l can be chosen even shorter than l_w. In Fig. 3c, it is stretched to equal L as before. In this case roughness is considered to be the totality of all shaded areas between the effective profile p_i and the center line m. Therefore, there is no strict and unique discrimination between roughness and other surface deviations.

In countries using the envelope or E-system, such as France, Italy, Switzerland, and Germany, the envelope profile p_e, Fig. 3d, serves as reference lines; e.g., see (2),(6). In this system the roughness is defined as the deviation of the effective profile p_i from the envelope profile p_e. The latter, as already shown, represents the upper limit for roughness and the lower limit for waviness. Therefore, in the E-system, the shape deviations of the 2nd order (class) are effectively separated from those of a higher class (roughness). There are no difficulties here in proceeding from the two-dimensional to the three-dimensional concept of roughness. It is only necessary to replace the terms effective profile and envelope profile by the terms effective surface and envelope surface.

The existence of parallel systems (M- and E-systems) has led the ISO-Committee TC 57 to the regrettable necessity of establishing definitions for the E-system similar to the definitions for the M-system given in ISO-Rec. 468 (7).

<u>Step III</u>: Because of the lack of a generally accepted classification of shape deviation, it follows that it is impossible to systematize the definitions of surface measurement parameters at the present time. Therefore, the parameters for form errors, waviness and roughness coexist rather incoherently. This fact has led to very heterogeneous definitions in the different countries, and even in the ISO-Recommendations (3),(7). All existing practices are restricted to the evaluation of profile sections. Only in Germany have efforts been made to develop a three-dimensional analysis of the surface.

The standardization of singular and integral parameters for roughness is by far the most advanced, but it has little relation to other geometric deviations. In Table 1, the definitions for some important national and international standardized roughness parameters are given.

The primary roughness parameter in the M-system is the arithmetical average height R_a (AA, CLA). In the E-system, it is the envelope average depth R_p which gives much more information than R_a. In both systems other singular roughness parameters are used (R_t, R_{max}, PVH). In addition to the roughness parameters listed in Table 1, many other parameters are mentioned in the different national standards such as the root mean square height R_q = RMS (USA), the average valley depth R_v (Switzerland), the average crest depth R_s (Switzerland), the profile depth H (Sweden), etc. Besides these characteristics there also exist some dimensionless roughness ratios such as the emptiness factor, form factor, the bearing area ratio, etc., which are defined quite differently in the different standards.

Much has been written on the advantages and disadvantages of the two reference systems. Until now, no universally acceptable rule has been found. Parameters for form deviations and waviness that are analogous to those of roughness are still nonexistent.

In summary, it can be said that a review of all existing national standards reveals an extremely unsatisfactory state, as follows:

1. Except for the German efforts (DIN 7182, Paper 4 (1)), I know of no attempt in any national standard to comprehensively define the particular classes of deviations on a three-dimensional basis instead of a two-dimensional basis.

2. In spite of the fact that form deviations (shape deviations of the 1st order (class)) do not differ basically or in principle, only in size, from the other classes of shape deviations; until now, they have been regarded from quite other points of view.

3. Parameters for waviness (shape deviations of the 2nd order (class)) corresponding to those of roughness can be found only to a modest degree in a few standards. The reason is that in the M-system, such an analogy to roughness is not possible.

4. According to SCHMIDT (8), complete confusion exists on the definition of roughness in at least 23 national standards.

<u>Step IV</u>: As there exists no obligatory and logically organized set of definitions, either for the different classes of geometric deviations or for the corresponding parameters, uniform methods of measurement that will allow measurement of shape deviations of different classes do not exist.

1. Form deviations, waviness, and roughness of a surface are alike in their essential features. They differ only with respect to their horizontal dimension or wavelength. Therefore, it would be natural to measure their parameters in the same way, at least in the two-dimensional method. That this has not been done, up to now, is based on fact that the traditional concepts prevent a clear discrimination of the different classes. Consequently, there co-exist instruments for the measurement of form deviations (e.g., roundness and flatness), waviness and roughness that have no possible application to measurements of the other classes. Only recently can some progress in this direction be seen.

2. Regarding specifically the measurement of roughness, it must be noted that, except for the E-system, methods of measurement that correspond exactly to the definitions do not exist. Only by means of certain, somewhat questionable procedures, can measurements be obtained that are more or less good approximations to those values that should be found according to the standard.

In industrial practice, roughness measurements are made almost exclusively by electromechanical tracer instruments. These instruments differ in mechanical design (e.g., with respect to radius of the stylus, the stylus pressure, and tracer speed) as well as in electrical performance (inductive and piezo-electric generator types on one hand and inductive or capacitive carrier frequency types on the other hand). So that, in addition to the difficulties caused by the variety in the kinds of parameters, the different types of instruments determine the same parameter in entirely different ways and in different units. Furthermore, it is very disturbing that the filter used in the instruments has no uniform transmission characteristic and that the sampling lengths used are very different.

Under these circumstances, it is not surprising that on the same specimens and the same profile section, the different instruments give widely differing roughness values as was shown in detailed investigations by LUEG and KRAUSE (9), by KRAUSE and PAWELSKI (10) and others. These discrepancies in the indications of instruments have often led to troublesome differences of opinion on the quality of the product between the producer and the customer. All M-system instruments determine the values with respect to an electrical zero line which does not in any fashion correspond to the standard center or mean line, as demonstrated by WHITEHOUSE and REASON (11). Of course, values obtained by such instruments cannot correspond to those that are found on the same profile by planimetering. Instruments based on the E-system that are now commercially available, Figure 4, use the envelope and the form profile as reference lines. They locate these reference lines continuously at each point of the surface within the sampling length in a unique manner and determine the R_p -values according to Fig. 3d. In this way the conformity of the measured R_p -values with the values found by standard planimetering methods is assured.

Specifications relating to the performance of measuring instruments can be found in only a few national standards. Until now, such specifications have been avoided in the German standards, because generally acceptable concepts have to exist first on what properly should be measured. Some specifications are given in the British standard B.S. 1134: 1961 (4) that assure a consistent measurement of the R_a - (CLA-, AA-) values. These specifications fix certain values for the filter cut-off wave-length, the sampling length, the stylus force, and the form and size of the diamond stylus. In addition, some practical measurement procedures are given. The American standard ASA B 46.1-1962 gives specifications on mechanical properties (such as radius of the stylus tip, stylus pressure, sampling length, construction of skids) and on the required electrical performance (frequency band width, cut-off, indicating meters) of the instruments.

The remarks on Step IV must be closed by noting that much development work is yet to be done in the metrology of surface finish, and in order to do this, it may be necessary to break with traditional thinking.

Step V: The inconsistency of the different national standards is reflected in engineering drawings by the heterogeneous remarks concerning the required surface quality. Form deviations are characterized from a viewpoint that is basically different from that applied to roughness. To the best of my knowledge, form is specified in terms of form deviations: roundness, flatness, concentricity, etc. The specification of roughness was originally confined to an appropriate qualitative characterization by means of certain symbols, for example, by groups of triangles (Germany, Austria, and others) or circles (Netherlands) or by a single triangle with an inscribed symbol for the manufacturing process (Great Britain). After the establishment of certain roughness parameters and of preferred ranges for the corresponding numerical values, the designer gradually turned to a quantitative characterization. Out of consideration for the millions of existing drawings that could not be changed, initial attempts in some countries, e.g., Germany, consisted of giving the groups of triangles a quantitative sense. Difficulties were encountered because over the years each industrial plant had given different quantitative weights to these symbols. As a result, the attempt to correlate a single roughness (R_t -) value to each triangular symbol did not succeed. Therefore, in the German standard, DIN 3141 (12), four different series of roughness (R_t -) values were correlated with each triangular symbol. In this way, it was only necessary to indicate, in the old drawings, to which series the triangular symbols should correspond.

Experience has shown that it is advantageous to use different roughness parameters for different purposes. Therefore, means for indicating on drawings the admissible roughness values associated with different roughness parameters had to be created. The American standard ASA B 46.1-1962 (5) and the British standard B.S. 1134: 1961 (4) permit a numerical characterization of roughness only by R_a - (CLA-, AA-) values whereas the German standard DIN 3142 (13) allows roughness to be numerically fixed by means of a variety of parameters for which in DIN 4763 (14) values corresponding to various grades are given. In contrast, the American standard (5) gives a means of indicating the waviness height, the waviness width and the roughness width. ISO-Rec. 468 permits only the specification of R_a- and R_z-values. An additional complication is the confusion between metric and English units. The variety of existing methods for specifying surface geometry makes the reading of foreign drawings very difficult and often a direct translation is not possible. Misinterpretation creates difficulties, errors, misunderstandings, and product rejections.

In reviewing the unsatisfactory conditions described in Section 3 of this report, it is not surprising that evaluations of the same surface by different people produce contradictory results.

The deficiencies of the existing definitions, specifications, and standards create many problems in research where surface finish is of importance. As long as the different institutes speak different technical languages, experimental results cannot be compared, no matter how carefully the measurements may have been made. Progress on a metrological, typological, or functional surface problem is handicapped by the difficulties of assimilating the results from different investigations. All scientists whose work involves the measurement of surfaces should, therefore, cooperate in the development of a systematic approach to total surface metrology.

4. THE DIRECTION OF NEW DEVELOPMENTS

The unsatisfactory conditions described in the preceding section have inspired various professionals to work toward an improvement and unification of the standards.

In Germany, the initial efforts, illustrated in Fig. 3a to d, to obtain a uniform consideration and evaluation of all geometrical deviations have been extended (15). One method of establishing a consistent system of classes of geometrical deviations is shown in Table 2, along with the parameters that must be defined. Presently, the available definitions are limited to the two-dimensional case; hence, to the evaluation of profile sections. It would be possible, however, to establish definitions for the three-dimensional case also. The difficulty to be overcome in the development of three-dimensional concepts are obvious. However, the history of science shows that such problems have provided the necessary incentive that leads to a technical breakthrough. It is to be hoped and anticipated that such will be the case here.

Meanwhile, it is generally recognized that a surface cannot be described by a single roughness or waviness parameter. The complex character of the surface suggests analysis of the surface by means of statistical and electronic methods; either directly, i.e., during the measuring process, or indirectly, by profile plotting in accordance with advanced viewpoints. Usually, the results of such investigations are mathematical functions or curves characterizing the surface profile. For example, the following curves can be obtained from the effective profile:

1. The well-known bearing area curve described by ABBOT.

2. The amplitude density curve, Fig. 5, found by differentiation or by direct measuring methods, first used experimentally by PESANTE (16).

3. The frequency distribution curve.

4. The correlation function, which has been used extensively by PEKLENIK (17); and finally

5. The slope distribution, also described by PEKLENIK.

These curves can be conveniently obtained by digital computer analysis of profile curves recorded on punch tapes (17),(18), or magnetic tapes (19). The correlation function, Fig. 6, discriminates between the periodic and random components of the profile suggesting a means of typological surface classification (20). Similar investigations based on the E-system are to be conducted at the Technical University of Braunschweig. Parallel with these investigations of typology are those of the standardization of surface measurement methods.

In this effort, it is necessary to find standard ways and means for calibrating existing instruments (21). The OECD committee "Surface Quality Control" has started investigations on this problem. These investigations involve the comparison of results obtained from a variety of instrument types when measuring standard surface specimens. In addition to the well-known standard surfaces with periodically repeated grooves of known geometry (NPL glass standards, cali-blocks), reference standards developed by the Physikalisch-Technische Bundesanstalt (22), Fig. 7, are also used. The latter standards, like the former, have parallel grooves, but in contrast to the former, the depths of the grooves are random rather than regular. The only periodicity in these specimens is a repeat of the profile in each sampling length of the measuring instruments. It is expected that the OECD tests will reveal significant differences in measured values because of the different methods of signal generation and processing. This will probably cause considerable pressure for action on a standardization of instrument types. This effort should proceed considering a course of logical development and practicality. In this regard, it is regrettable that the ISO/TC 57 is restricting itself to standardization of roughness and waviness and is not seeking a standard definition for form deviation. Furthermore, the ISO-Rec. 468 (7) is restricted to the M-system. Working Group 1 of ISO/TC 57 is at present working on a draft of a recommendation based on the E-system. Working Group 2 is engaged in standardizing calibration standards for surface roughness meters and comparison specimens for subjective surface testing.

5. SUMMARY

This paper has attempted to show that existing national and international standards and specifications do not satisfy the requirements of a universal method for describing the different geometrical deviations of a surface. In addition, an approach that leads to the establishment of such a universal system has been proposed.

More attention should be given to the three-dimensional concept of the surface. The complex nature of the surface has recently led to the development of statistical methods of surface analysis that will hopefully, in turn, lead to new discoveries. Standardization of measuring methods for roughness and waviness is urgently needed in order to improve the communication of results of surface-related research. Further international cooperation is needed in order to solve the many existing problems of surface metrology.

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Table 1

Definitions of the most important national and international standardized roughness criteria (parameters)

Name of the criterion in the original language	Standard	Country	Symbol of the criterion	Definitions according to the M-system (Fig.3c)	Definitions according to the E-system (Fig.3d)
Centre line average height	B.S.1134:1961	Gr.Britain	CLA	$\frac{1}{l}\int_o^{l} \lvert a \rvert dx$	—
Arithmetical average height	ASA B 46.1-1962	USA	AA		
Arithmetical mean deviation	ISO Rec. 468	internat.	R_a		
Mittenrauhwert	DIN 4762	Germany	R_a	—	$\frac{1}{l}\int_o^{l} \lvert c \rvert dx$
Ten point height	GOST2789-59	USSR	R_z	$\frac{(h_1+h_2+\ldots h_5)-(h_6+h_7+\ldots h_{10})}{5}$	—
Ten point height	ISO Rec.468	internat.	R_z		
Glättungstiefe[1)]	DIN 4762	Germany	R_p	—	$\frac{1}{l}\int_o^{l} y\, dx$
Mittlere Rauhtiefe[1)]	VSM 58300	Switzerland	R_p		
Profondeur moyenne[1)]	E 05-001	France	R_p		
Rauhtiefe[2)]	DIN 4762	Germany	R_t	—	y_{max}
Maximale Rauhtiefe[3)]	VSM 58300	Switzerland	R_{max}		
Peak to valley height	B.S.1134:1961	Gr.Britain	-	h_1-h_6	
maximum height	ISO Rec. 468	internat.	R_{max}		

1) Envelope average depth (levelling depth); 2) Total roughness depth; 3) Maximum roughness depth.

TABLE 2

Definitions of the different classes of shape deviations and their numerical evaluation

Order of the shape deviation	Definition	Surface parameters (criteria) for the Maximum value	Surface parameters (criteria) for the integral value
1 st Class: form deviation (error of form)	Deviation of the form profile p_f from the adjacent profile p_s (Fig. 3a)	total form depth $F_t = y_{f\,max}$	average form depth $F_p = \frac{1}{L}\int_0^L \quad dx$
2nd Class: waviness	Deviation of the envelope profile p_e from the form profile p_f (Fig. 3b)	total wave depth $W_t = y_{w\,max}$	average wave depth $W_p = \frac{1}{l_w}\int_0^{l_w} y_w \, dx$
3rd to 5th Class: roughness	Deviation of the effective profile p_i from the envelope profile p_e (Fig. 3d)	total roughness depth $R_t = y_{r\,max}$	envelope average depth (levelling depth) $R_p = \frac{1}{l}\int_0^l y_r \, dx$ additional average roughness depth $R_a = \frac{1}{l}\int_0^l \lvert c \rvert \, dx$
Sum of all deviations	Deviation of the effective profile p_i from the adjacent profile p_s	total shape deviation $D_t = (y_f + y_w + y_r)_{max}$	average shape deviation $D_p = F_p + W_p + R_p$

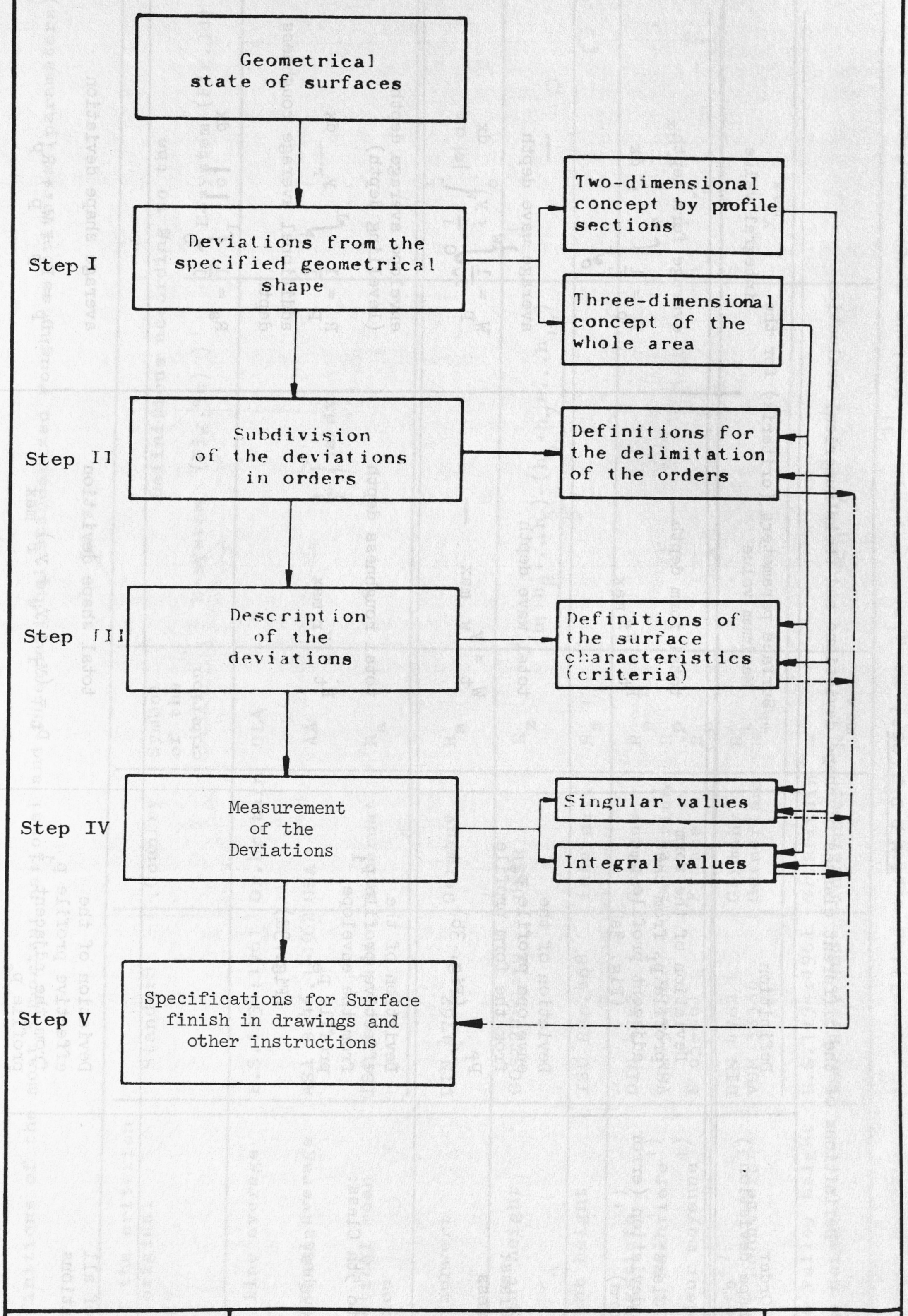

Fig. 1: Scheme for a methodical proceeding for the evaluation of the geometrical state of surfaces.

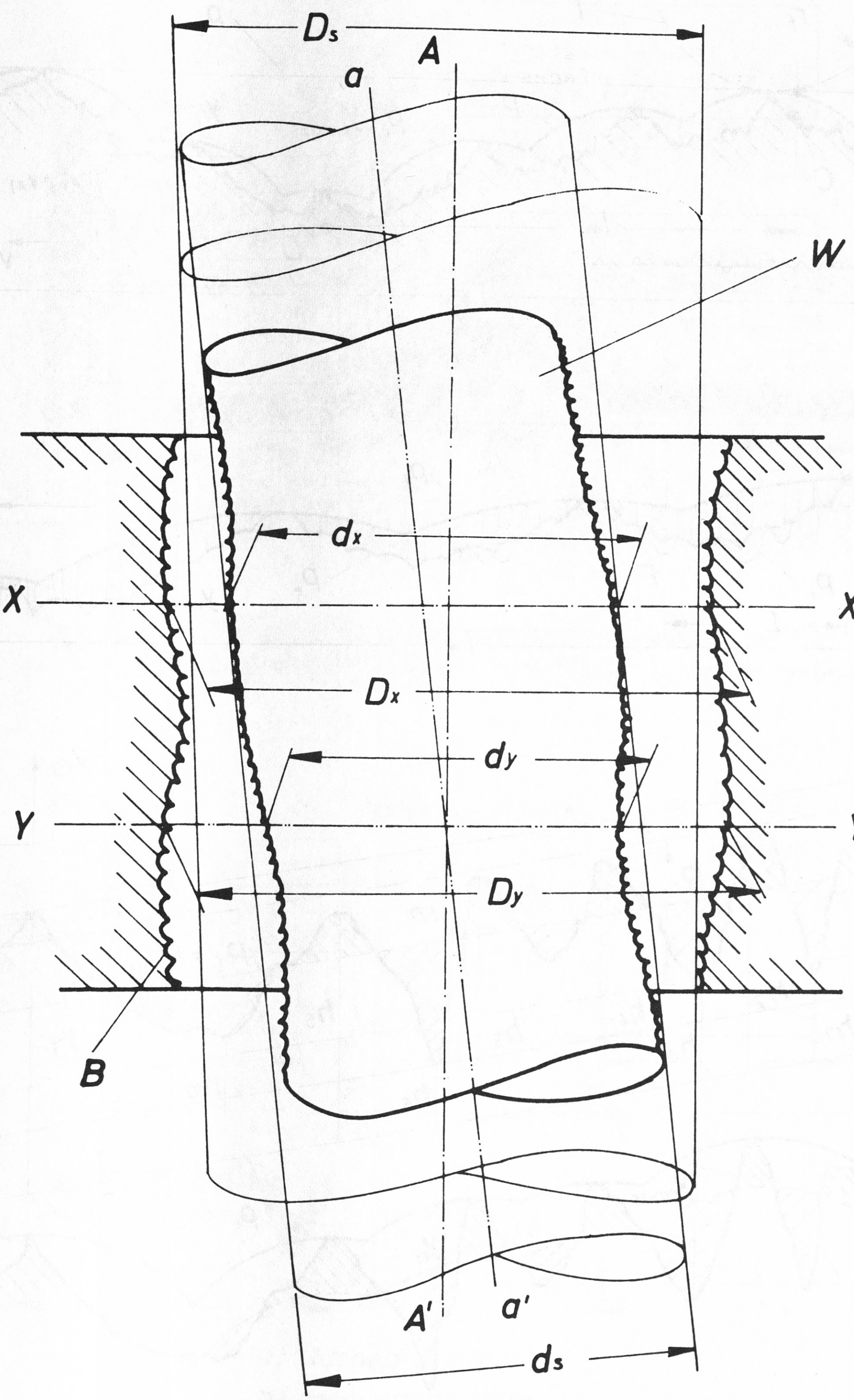

Fig.2 Determinations of the clearance between two workpieces with shape deviations by means of their adjacent cylinders.

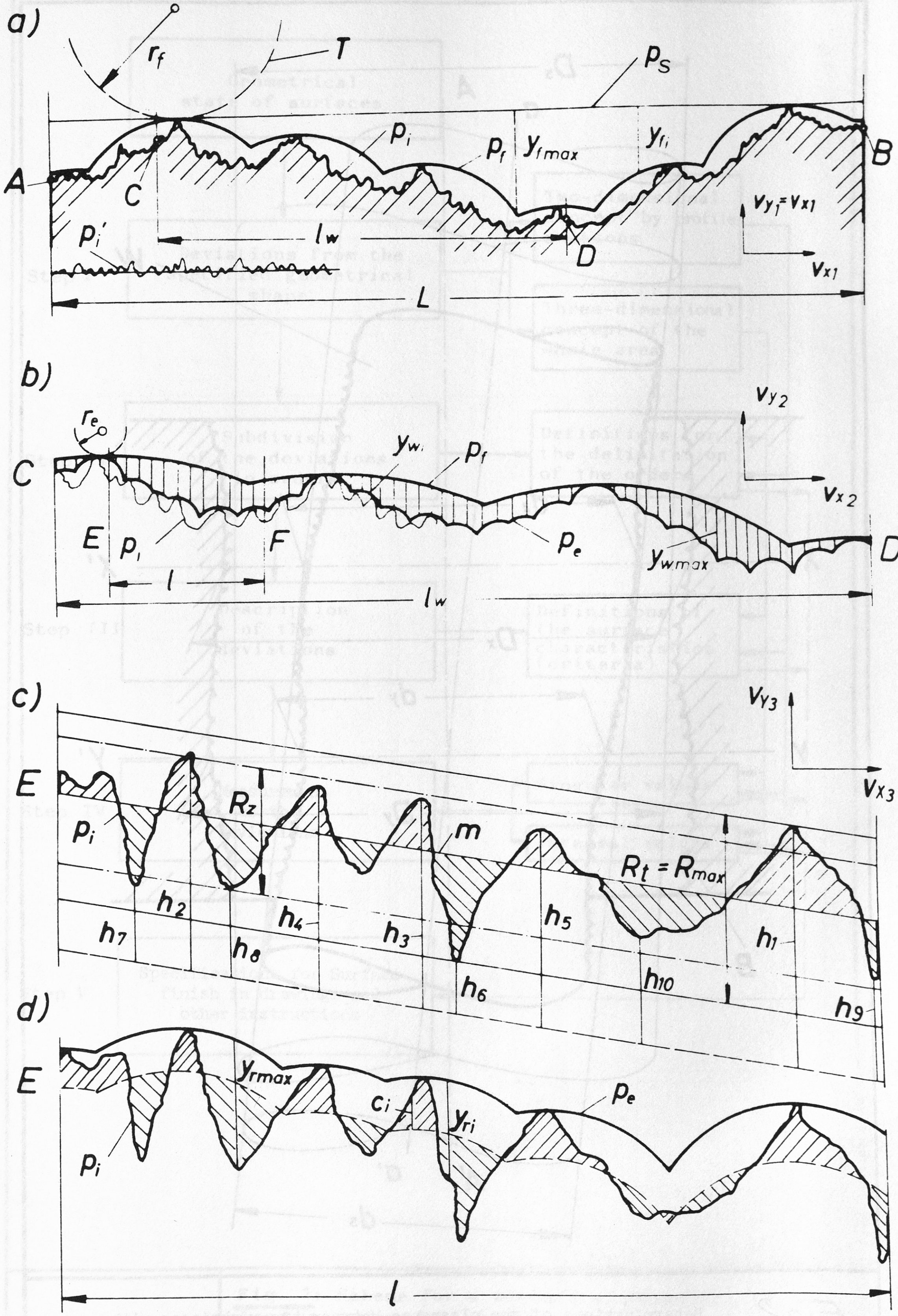

Fig. 3 a) to d). Analysis of the shape deviations according to different orders (classes).

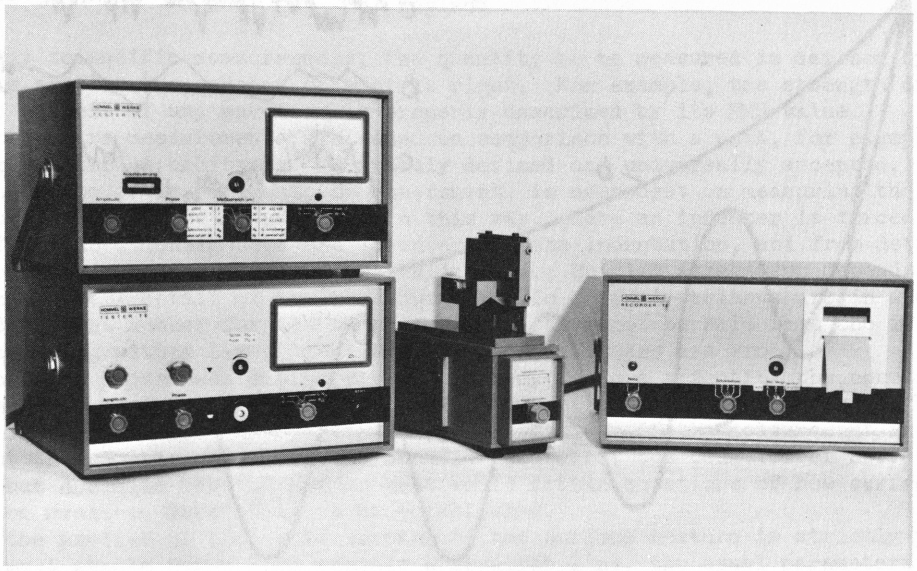

Fig. 4 Two-stylus instrument for measurements of roughness or waviness according to the E-system.

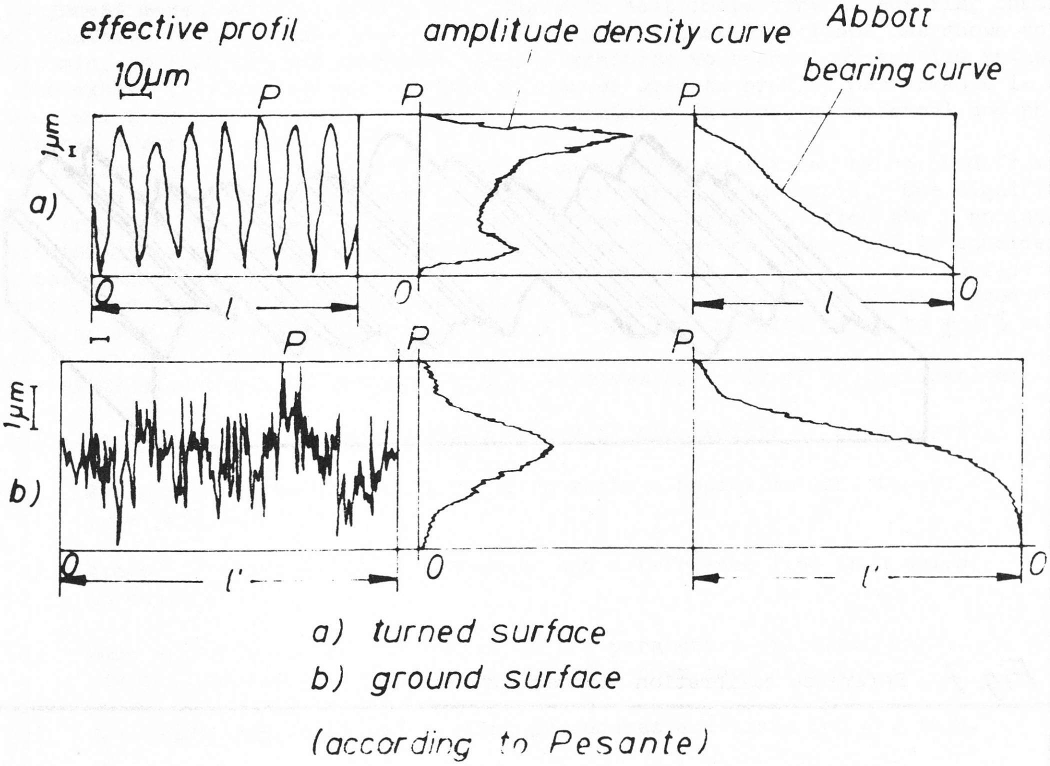

Fig. 5 Amplitude density curves and ABBOTT's bearing curves (after PESANTE).

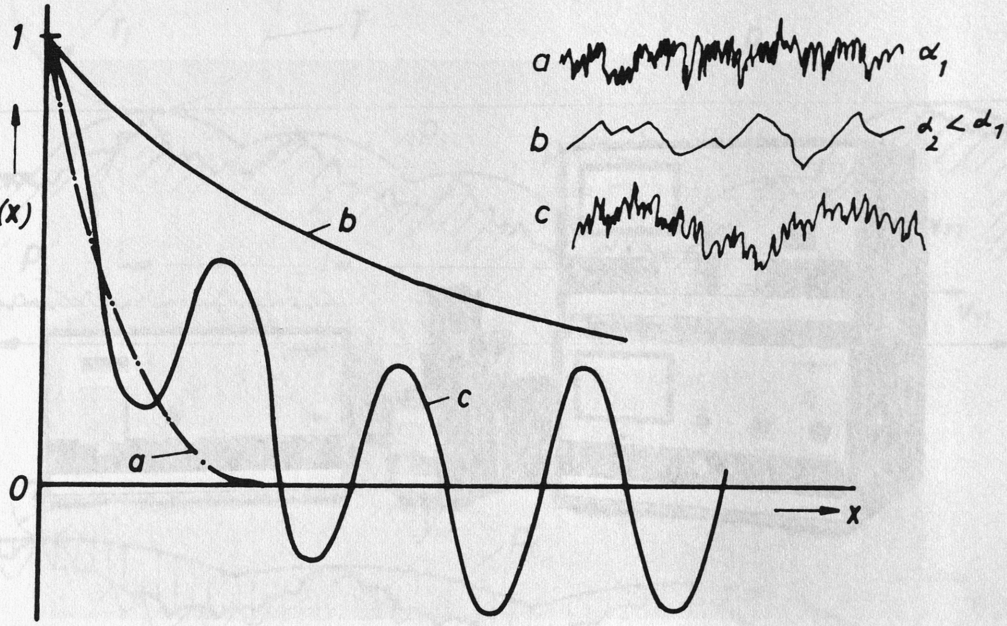

Fig. 6 Correlations functions of surfaces with different profile character.

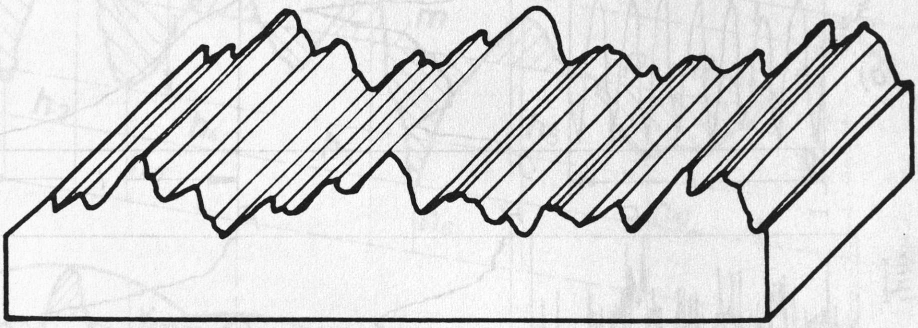

Fig. 7 Reference calibration standard of the PTB.