

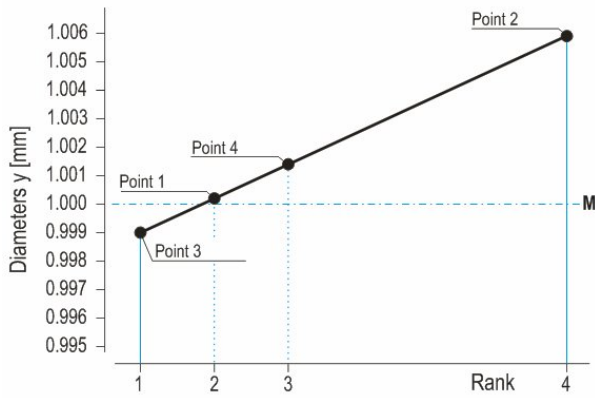
D. Dengel, H. Fischer, H.-P. Vollmar

The FACTORY DIAGNOSIS DIAGRAM – An Efficient Tool for Quality Control

During electroplating or heat treatment operations parts are usually mounted on plating or charging racks, which can for practical purposes be described as position matrices. An optimized production process should exhibit no significant changes in the quality characteristics of the products after going through the production cycle regardless of the product's position within the matrix. Measurement results taken from a random sample of finished parts over a number of predetermined rack locations can be displayed easily in a Factory-Diagnosis-Diagram (FDD®), which is introduced in this paper. The descriptive nature of this type of diagram truly provides an "at a glance" display of essential quality related information. Weaknesses in a manufacturing process or a production line become evident, without the need for complex data analysis. The advantages of the Factory Diagnosis Diagram, highlighted in this paper can be applied beyond example application to nearly all areas of production.

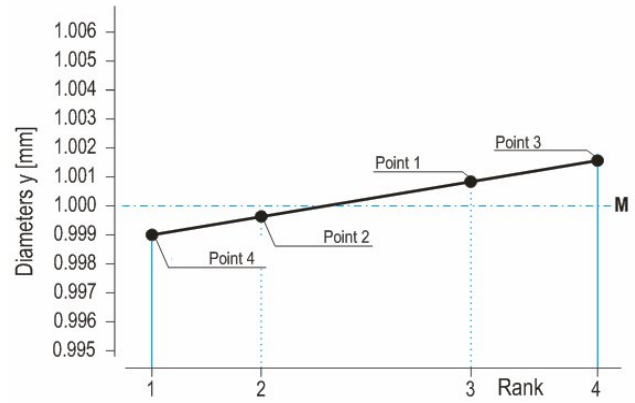
1 Introduction

As a rule, counting, measurement and experimental data of various origins are initially protocolled or stored in the order of their occurrence. For descriptive and/or analytical processing of such data, it is often advantageous, at times even mandatory, to sort the data in ascending or descending order according to their size, i.e., to bring them into a so-called rank order. In particular, in applied statistics, rank orders form the foundation for certain evaluation methods or graphical presentations, for example in probability charts, cf. [1-3].



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 1	Point 3
∅ 0.9990 mm	∅ 1.0002 mm	∅ 1.0014 mm	∅ 1.0059 mm

Fig. 1. Rank order of diameter values measured on four specified places of a defined pin



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 1	Point 3
∅ 0.9990 mm	∅ 0.9997 mm	∅ 1.0008 mm	∅ 1.0016 mm

Fig. 2. Analogous to Fig. 1: Rank order of a further pin after realizing a quality improvement

Apart from these special applications, such rank orders are most often expressed only in table format. Only rarely is use made of the remarkable possibilities of, for example, quickly acquiring additional valuable insights by displaying (simultaneously) the rank data in the form of so-called rank diagrams. This is surprising considering the manifold possibilities of applying such presentations in the broad field of quality management. Both in production control as well as in receiving, interim and outgoing inspections, they prove to be extremely efficient tools for quick, reliable and at the same time economical product and process evaluations (“quality diagnoses”), as shall be demonstrated below.

In this paper, the displaying of measurement results in the form of a special rank diagram type called Factory Diagnosis Diagram (FDD^{®1}) is introduced and explained with regard to its significant advantages and characteristics. This type of diagram is applicable in many areas of application as a simple yet efficient instrument of quality management. Its distinctive feature is that the test results of a certain quality feature, which is demanded to be of the same value at several locations of a product, are fundamentally always reproduced as a plot in the form of a straight rank line. This simple presentation method allows the specialist to arrive at quick and remarkably reliable information regarding the current production quality without the need for additional evaluation steps.

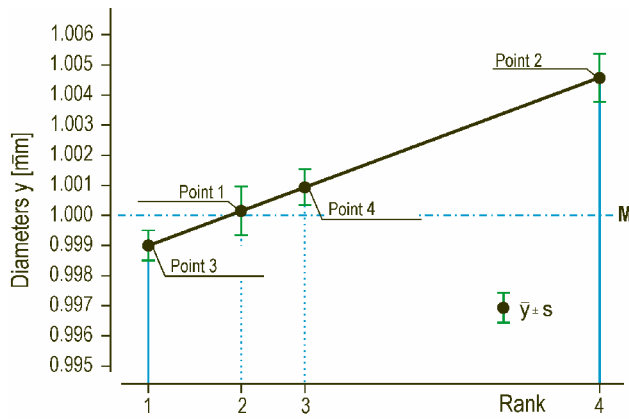
¹ Ref. [4]

2 The Factory Diagnosis Diagram

2.1 Fundamentals

The Factory Diagnosis Diagram is a rank diagram type that presents a pre-specified number of measurement data or characteristic quantities in an ascending order *linearized* as points $\{y\}$ over the assigned ranks $\{x\}$. To this end, it is simply necessary to establish on the abscissa (rank axis) a suitably selected distance (to be kept the same for comparative presentations) between the respective first and last rank (rank distance) of the examined group of data.

How to arrive at a Factory Diagnosis Diagram can be demonstrated in a simple manner using the manufacture of pins for needle bearings as an example: For a pin, (target length $L = 20.00$ mm; target diameter $D = 1.000$ mm) taken from a defined location, a diameter value is determined according to the test instructions at four equally spaced measurement locations, namely at 4 mm, 8 mm, 12 mm and 16 mm, with the reading carried out to $0.1 \mu\text{m}$ (“estimation point”); this provides the following result, Fig. 1. The diameter reading at 8 mm (2nd measurement location) deviates in a “significant” (systematic) manner – here initially according to a subjective evaluation – and results, therefore, in the relative “steep slope” of the straight rank line. A readjustment of the production machine, carried out as a result, leads to a recognizably “better” result for the next pin, Fig. 2. The slope of the rank line is significantly less steep; in addition, the (changed) order and more uniform distribution of the measurement results over the rank distance suggest that the differences between local diameter readings are “purely coincidental”. “At a glance” one is able to draw the conclusion of a “quality improvement”.



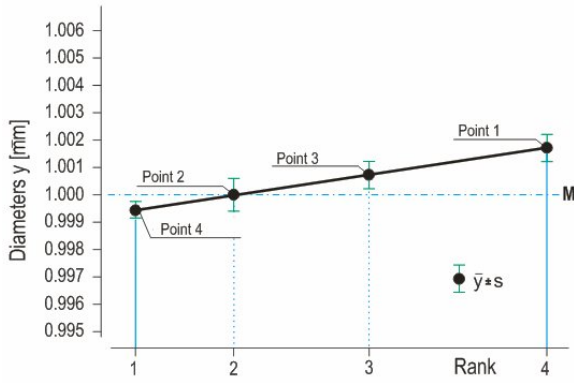
Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 3	Point 1	Point 4	Point 2
$\bar{y} = 0.9990 \text{ mm}$	$\bar{y} = 1.0001 \text{ mm}$	$\bar{y} = 1.0009 \text{ mm}$	$\bar{y} = 1.0046 \text{ mm}$
$s = 0.0005 \text{ mm}$	$s = 0.0008 \text{ mm}$	$s = 0.0006 \text{ mm}$	$s = 0.0008 \text{ mm}$

Fig. 3. Rank order of \bar{x} , s -values ($n = 4$) obtained at four specified places of a defined pin

To increase the reliability of the information, the “testing accuracy” has been raised for this production by carrying out four diameter measurements at each of the four positions mentioned, each time advancing the angle by 45° . The four diameter values at each longitudinal position can be interpreted as random samples (sample size $n = 4$), because the advance in the angle was not carried out against a defined starting point. One can deduce from Fig. 3, again at a glance so to speak, that the diameter at the 2nd measurement location (i.e., at 8 mm) deviates significantly and not randomly from the other measurement locations. The measurement data scatter (“scatter bar”), visualized using the standard deviation ($\pm s$), does not indicate significant scatter differences between the four measurement locations.

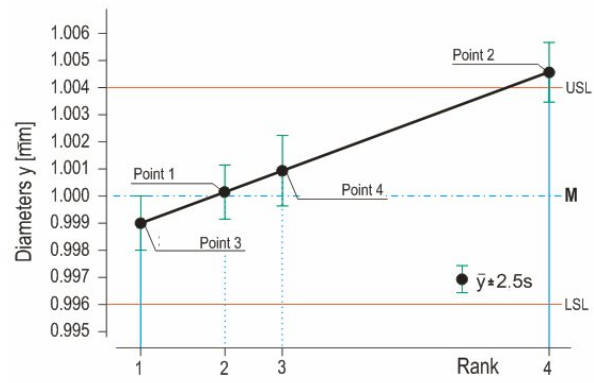
The necessary readjustment of the production machine provided a significantly “better” result, ref. Fig. 4. With a comparable scatter of the diameter values at the four measurement locations, the mean values are now distributed with a satisfactory uniformity across the length of the “gently” increasing rank line of the Factory Diagnosis Diagram.

In many cases, maintaining a tolerance is required for the quality feature under observation. In the example above, the specification limits for the pin diameters were determined with 1.004 mm (USL = upper specification limit) and 0.996 mm (LSL = lower specification limit).



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 3	Point 1
$\bar{y} = 0.9995 \text{ mm}$	$\bar{y} = 1.0000 \text{ mm}$	$\bar{y} = 1.0008 \text{ mm}$	$\bar{y} = 1.0018 \text{ mm}$
$s = 0.0003 \text{ mm}$	$s = 0.0006 \text{ mm}$	$s = 0.0005 \text{ mm}$	$s = 0.0005 \text{ mm}$

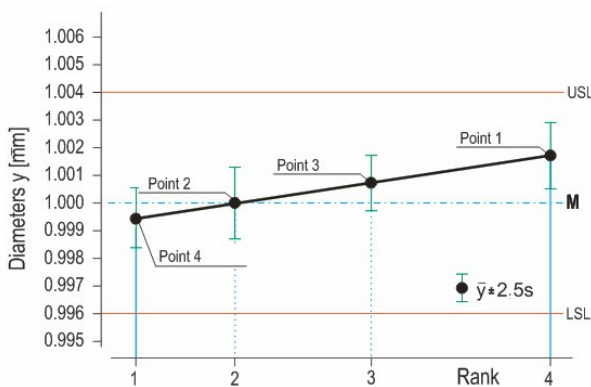
Fig. 4. Analogous to Fig 3: Rank order of a further pin after realizing a quality improvement



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 3	Point 1	Point 4	Point 2
$\bar{y} = 0.9990 \text{ mm}$	$\bar{y} = 1.0001 \text{ mm}$	$\bar{y} = 1.0009 \text{ mm}$	$\bar{y} = 1.0046 \text{ mm}$
$2.5s = 0.0010 \text{ mm}$	$2.5s = 0.0010 \text{ mm}$	$2.5s = 0.0013 \text{ mm}$	$2.5s = 0.0011 \text{ mm}$

Fig.5. Analogous to Fig. 4: Introduction of specification limits

A violation of specification limits cannot be excluded if – and this shall initially serve as a rough rule of thumb – in a Factory Diagnosis Diagram the end points of the one-sided scatter bar reach $(\bar{y} + 2.5 s)$ the USL or $(\bar{y} - 2.5 s)$ the LSL “from the inside” (tolerance). Fig. 5 shows that the tested pin not only exceeds the USL clearly at the 2nd measurement position but even with its mean diameter \bar{y} . This means that here several single readings are above the USL, which makes corrective measures (readjustments) unavoidable. In comparison to Fig. 5, Fig. 6 shows an overall satisfactory result for a sample pin that has been taken after the readjustment.



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 3	Point 1
$\bar{y} = 0.9995 \text{ mm}$	$\bar{y} = 1.0001 \text{ mm}$	$\bar{y} = 1.0008 \text{ mm}$	$\bar{y} = 1.0016 \text{ mm}$
$2.5s = 0.0011 \text{ mm}$	$2.5s = 0.0013 \text{ mm}$	$2.5s = 0.0010 \text{ mm}$	$2.5s = 0.0012 \text{ mm}$

Fig. 6. Analogous to Fig. 5: Rank order of a further pin after realizing a quality improvement

The simple application example mentioned above already indicates the enormous potential inherent in the Factory Diagnosis Diagram. Today, for almost any measuring application, the employed measurement device is capable of providing the obtained measurement data directly (online, wireless) to a PC, where they can be evaluated in just a second and displayed in a clear fashion as a Factory Diagnosis Diagram. Position, slope and point arrangement of the rank line as well as the size and the uniformity of the associated scatter bars can be evaluated at a glance, so to speak; thus, it is often possible to do entirely without simultaneous analyses of measurement and evaluation tables. Thus, presentations in the form of Factory Diagnosis Diagrams enable the practitioner to arrive at a quality diagnosis quickly and reliably, without requiring of him the often tedious use of complex statistical evaluation methods.

2.2 Factory Diagnosis Diagram: "Auto body coating"

2.2.1 Preliminary Remarks

For the application example (pin diameter) described in Section 2.1, "multi-sectioning" of the evaluated product was a result of the requirements (test instructions) to perform the diameter measurements at four measurement locations along the length of the pin. For this reason, four "ranks" each formed the foundation for the Factory Diagnosis Diagram. This is comparable, for example, to the conditions on boards (generally: Flat products) with certain dimensions, perhaps made of metal or plastic, where the same target value for a quality feature, which is measured only discretely (i.e., not continuously) due to metrological economic reasons, is required for all locations. Here, multi-sectioning is the result of the number of measurement locations (e.g., marked board areas), which are specified for specific cases by the quality requirements. This situation is often found when monitoring the material thickness or when verifying certain characteristic values at various kinds of coatings (mechanical, chemical, thermo-chemical). In particular in electroplating, product racks used for the transport through the bath are often divided into sections in order to recognize systematic differences that might occur in an often ambiguous manner at objects that have been removed from these racks specifically for this purpose after the coating process; this can be due to the position of the anode, the bath movement, a reduction in the field or even because of a power down.

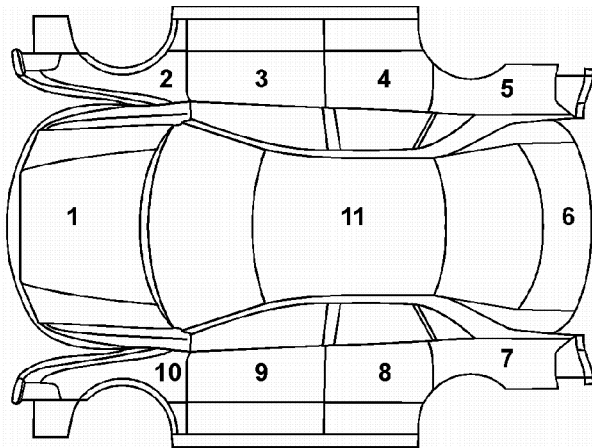


Fig. 7. Top view of an auto body (butterfly diagram)

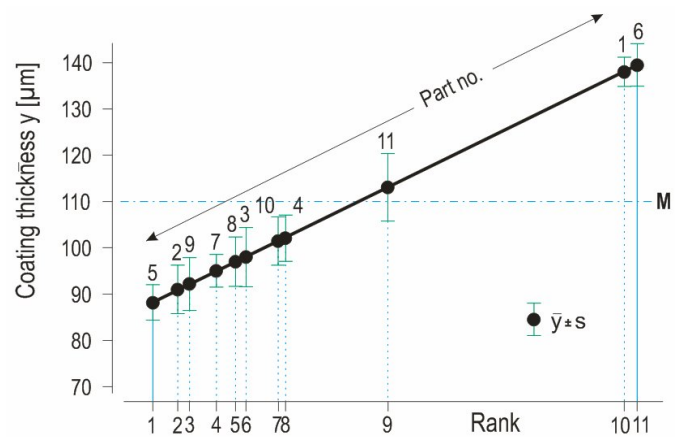


Fig. 8. Factory Diagnosis Diagram of an auto body based on the evaluation values of Table 1

The findings of such examinations then form the foundation for quality improvements for both products and process management. A corresponding practice offers itself in the field of technical heat treatment when examining the uniformity of certain furnace batches, where it is possible to evaluate quickly not only the batch quality itself but simultaneously the quality of the furnace system as well.

Even if different target values for the examined quality feature are specified for special products from one partial section to another, a normalization of the measurement results for differences (e.g., of the type: (local) target value minus measured value) would – in principle – not change anything for the presentation of the Factory Diagnosis Diagram.

2.2.2 Practical Example

For auto bodies, the multiple sections explained above arise practically “by themselves”, ref. Fig. 7. For the $k = 11$ (essentially clockwise) consecutively numbered individual parts of the auto body evaluated here, the thickness of a new type of coating structure (target value $d = 110 \mu\text{m}$) was to be monitored in the course of a pilot trial; according to test instructions following a specified measurement plan, $n = 5$ measurements were to be performed for each individual part.

Coating thickness y in μm	Part designation	Part number	n	s	s	Rank ¹⁾ i
137, 133, 139, 141, 140	Engine hood	1	5	138.0	3.16	10
95, 87, 86, 89, 98	Front end right	2	5	91.0	5.24	2
98, 95, 103, 89, 105	Front door right	3	5	98.0	6.40	6
107, 103, 95, 99, 106	Rear door right	4	5	102.0	5.00	8
90, 83, 86, 89, 93	Rear end right	5	5	88.2	3.83	1
137, 143, 140, 133, 144	Tailgate	6	5	139.4	4.51	11
97, 93, 100, 91, 94	Rear end left	7	5	95.0	3.53	4
98, 95, 103, 89, 100	Rear door left	8	5	97.0	5.34	5
90, 87, 96, 89, 99	Front door left	9	5	92.2	5.07	3
103, 100, 110, 98, 97	Front end left	10	5	101.6	5.22	7
111, 117, 125, 109, 107	Roof	11	5	113.8	7.29	9

¹⁾ Ranks: $i = 1$ to $k = 11$

Table 1. Coating thickness of an auto body – measurement and evaluation results

Table 1 shows the measurement and evaluation results for a certain auto body; Fig. 8 shows the corresponding Factory Diagnosis Diagram. From it, it can be deduced (subjectively) that the scatter is not characteristically different from one body part to the next, however, that the mean coating thickness deviates significantly upward for two ranks. The body parts represented by these ranks are, therefore, responsible for the relatively steep slope in the rank line. If one additionally inserts the specified coating thickness tolerance (USL = 140 μm ; LSL = 80 μm) into the Factory Diagnosis Diagram, then it becomes immediately apparent (Fig. 9) that measures for improving the quality are recommended.

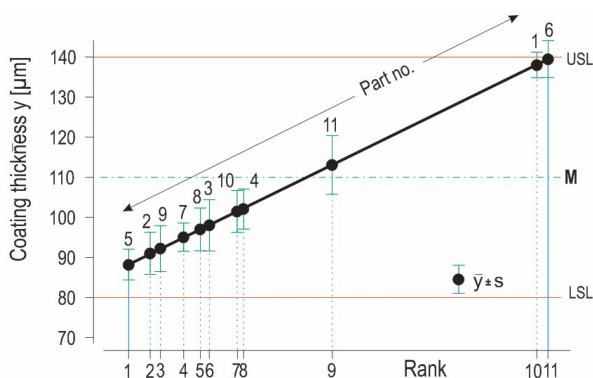


Fig. 9. Analogous to Fig. 8: Introduction of specification limits (USL / LSL)

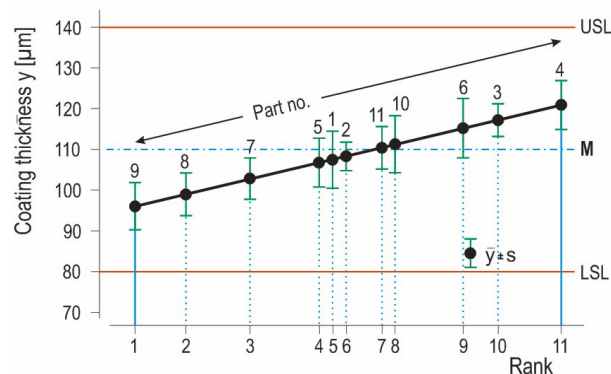


Fig. 10. Analogous to Fig. 9: Factory Diagnosis Diagram of a further auto body after realizing a quality improvement

At the end of these measures, the next auto body of this series provides the following Factory Diagnosis Diagram, ref. Fig. 10. The scatter of the coating thickness values of the individual parts has apparently not changed significantly. However, the rank

line now runs very satisfactorily within the tolerance, with the upper/lower ranks at a sufficiently safe distance from the respective relevant specification limits (USL / LSL). With this now significantly gentler slope of the straight line, the mean values are distributed in a satisfactory uniform manner along the rank distance as well. Thus, it can be concluded (subjectively) that there are no noteworthy (systematic) differences between the parts of this auto body with regard to the coating thickness. This condition of the system is to be maintained for the future.

In particular with “multi-part” Factory Diagnosis Diagrams, the clarity can deteriorate by labeling the individual points of the rank line (cf. Fig. 10, for example). In such cases, it is advisable to provide the appropriate part numbers at the respective (fixed) positions on the abscissa instead of the rank numbers. Thus, the rank axis can be converted easily into a part number axis without any loss of information.

3 Summary

The specialized rank diagram, described as the Factory Diagnosis Diagram (FDD®), can be understood as a succession of measurement data or characteristic data within a group, which has been ordered respectively beforehand with regard to its size, fundamentally presented in a *l i n e a r i z e d* manner in ascending order in an x/y coordinate system.

From the deliberations in this paper, it becomes apparent that the use of this special rank diagram offers itself essentially always as a diagnosis tool when practical solutions for quality management associated with manufacturing are considered. The term *multi-part* is to be interpreted expressly in the figurative sense such that at a “whole” (i.e., single part) product, a certain quality feature must be monitored simultaneously at several locations (fictitious: Parts) based on the specified manufacturing processes. For example, the bearing seats of a shaft that is supported at several places can be understood in the context of the Factory Diagnosis Diagram but also as individual parts, like the teeth or even defined tooth zones (e.g., the flanks) of a toothed wheel, or certain areas of furnace batches in the field of technical heat treatment, or certain contact locations of a specific electronic component. In many cases, the multi-part configuration is essentially apparent through the interaction between the means of production and the required product quality, as has been demonstrated on the practical example auto body in Section 2.2.

With suitable computer support of the measurement process, Factory Diagnosis Diagrams can be displayed on the screen essentially instantaneously with a click of the mouse as visualized test documentation. In all cases, the production and quality diagnosis derived from such diagrams is rather overall *negative* (ref. Fig. 12) if

- the slope of the rank line is relatively steep and/or
- the rank points can be divided into groups and/or
- tolerance violations occur or are beginning to show and/or
- the shown scatter bars are relatively great and/or
- the shown scatter bars are very irregular.

In all cases, the production and quality diagnosis derived from such diagrams is rather *positive* overall (ref. Fig. 13) if

- + the slope of the rank line is gentle,
- + the rank points can be interpreted as *one* group,
- + no tolerance violations occur or are beginning to show,
- + the shown scatter bars are relatively small, and uniform.

In most cases, a practitioner familiar with his manufacturing devices and quality features will quickly gain valuable insights simply based on a subjective evaluation of such Factory Diagnosis Diagrams that can help achieve significant and often sufficient progress in quality management. Through (optional) use of additional (statistical) evaluation routines it may, in some cases, be possible to gain additional significant insights. Such evaluation routines are already available as – user-friendly – software programs.

Bibliography

1. *Kühlmeier, M.:* Statistische Auswertungsmethoden für Ingenieure.
Springer-Verlag, Berlin, 2001, pages 163 ff.
2. *Storm, R.:* Wahrscheinlichkeitsrechnung, mathematische Statistik und statistische

- Qualitätskontrolle. Carl Hanser Verlag, München, 2001, pages 281 ff.
3. *Sachs, L.*: Angewandte Statistik. 7. Aufl., Springer Berlin, 1992, pages 371 ff.
 4. Offenlegungsschrift AZ 10 2004 052 302.9: Verfahren zur Ausgabe von Messwerten und Anzeigeeinrichtung. Helmut Fischer GmbH & Co. KG, Sindelfingen; German Patent and Trademark Office, 2006
 5. *Wilrich, P.-Th.; Henning H.-J.*: Formeln und Tabellen der angewandten mathematischen Statistik. 2. Aufl., Springer-Verlag, Berlin, 1987, pages 115 ff.
 6. *Eisenhart, Ch.; Hastay, M. W.; Wallis, W. A.* (Publisher): Selected Techniques of Statistical Analysis for Scientific and Industrial Research and Production and Management Engineering. McGraw-Hill, New York, 1947, Chap. 2, p. 97
 7. *Stange, K.*: Kontrollkarten für messbare Merkmale. Springer-Verlag, Berlin, 1975, pages 122 ff.

The Authors of this Paper

Prof. Dr.-Ing. *Dieter Dengel*, born 1937, studied Mechanical Engineering/Materials Technology and qualified as a University professor for the subject Materials Engineering. From 1970 to 2003, he was a university professor at the TU Berlin.

Helmut Fischer, born 1931, is the founder and managing director of Helmut Fischer GmbH with its headquarters in Sindelfingen, Germany. He has been active in the field of non-destructive coating thickness measurement since 1953.

Dr. rer. nat. *Hans-Peter Vollmar*, born 1959, studied physics and earned his doctor's degree in the field of semiconductor physics. Active from 1993 to 1998 as project director at ILK Dresden gGmbH (instrument development laser spectroscopy for atmospheric gas pollutant analysis), from 1998 to 1999 as Application Scientist at Rudolph Technologies Inc., New Jersey (coating thickness measuring systems in the semiconductor industry) and since the end of 1999 as department director in Development at Helmut Fischer GmbH.

The Manufacturer

HELMUT FISCHER GMBH
INSTITUT FÜR ELEKTRONIK UND MESSTECHNIK
Institute for Electronics and Measurement Technology
Industriestraße 21
71069 Sindelfingen, Germany
Tel. +49 (0) 70 31 / 3 03 - 0
Fax +49 (0) 70 31 / 3 03 - 79
mail@helmut-fischer.de
www.helmut-fischer.com

Company Profile

The Institute for Electronics and Measurement Technology HELMUT FISCHER in Sindelfingen/Germany is an innovative leader in the field of coating thickness measurement, materials analysis, microhardness testing, electrical conductivity- and Ferrite content measurement as well as for density and porosity testing. The company is able to recommend the best solution for any application. A comprehensive range of products is offered using X-ray fluorescence; Beta-backscatter; Magnetic; Magnetic induction; Electric resistance; Eddy current and Coulometric techniques. HELMUT FISCHER has 13 subsidiary companies and 34 marketing agencies strategically located around the globe.