Geometrical Product Specifications

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The need for a textbook that provides the fundamentals of dimensional and geometrical tolerancing was identified by the editor and his colleagues from other European universities during the International Conference on *Coordinate Measuring Technique* that is organised by Łódź Technical University the Bielsko-Biała Branch every two years. We furthermore discussed demands for such a textbook for students and lecturers in mechanical and production engineering faculties during the IMEKO World Congresses in 1999 in Osaka and in 2000 in Vienna.

I would also like to acknowledge the numerous colleagues from Technical Committee ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* and the national standards committees who have contributed much to our understanding of the current state of the art in dimensional and geometrical tolerancing.

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Zbigniew Humienny
Warsaw, July 2001

PREFACE

In this textbook we present the science of dimensioning, geometrical tolerancing and measurement of geometrical characteristics in a carefully structured manner which emphasises their foundations as well as their application. Most of the material covered in this textbook is regarded as appropriate for core bachelor and master student courses in mechanical and production engineering disciplines.

It is not intended that basic course lectures cover every point made in the textbook. Some topics are discussed more in details and it is believed that the parts of textbook are also highly suitable for more advanced courses.

The content of this textbook is based on the authors discussions, years of teaching experience and the curricula that are offered to students at:

- Institute of Machine Design Fundamentals, Warsaw University of Technology (Poland);
- Department of Interchangeable Manufacturing and Industrial Metrology, Vienna University of Technology (Austria);
- Department of Mechatronics, Tallinn Technical University (Estonia);
- Chair of Quality Management and Manufacturing Metrology, Friedrich-Alexander University Erlangen-Nuremberg (Germany);
- School of Engineering, University of Huddersfield (United Kingdom);
- Department of Manufacturing Technology and Automation, Łodź Technical University the Bielsko-Biała Branch (Poland).

All of the chapters' contributors are active researchers in the area and many are well known scholars whose research results have guided progress in their particular research field. Other contributors are young and promising scholars.

The objective of the authoring team has throughout, remained that of developing a model course for geometrical product specification that may be regarded as the basic textbook for teaching/learning at technical universities in Europe.

The authors have attempted to highlight the latest achievements and standards developed by ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* as well as by other ISO technical committees.

A novel feature of this textbook is the interactive CD that employs new information technology for teaching/learning and allows readers further study.

The text book is accompanied by the web page:

http://leonardo.simr.pw.edu.pl.

We encourage you to browse this web page to get the latest information in the GPS field as well as to send questions, comments and remarks to the autors.

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1 INTRODUCTION

S. Białas

When a machine part is being designed, the designer imagines it as an ideal, perfect object. According to designer's intent all dimensions and the shape (geometry) of the part are without geometrical error and the surface is smooth.

However, during machining an actual workpiece is created that is far from perfect. Its shape is distorted, dimensions are different from those imagined by the designer and the surface is rough. If many workpieces are manufactured according to the same technical drawing, each of them generally differs from others.

After machining the parts are assembled. This process is also not ideal and additional errors may occur. So the result of a manufacturing process is a real, not perfect product – a machine or a mechanical device. Despite manufacturing errors, the product may be regarded as acceptable if the errors are properly controlled.

A set of requirements concerning the geometry of a workpiece (or of an assembly of some workpieces) is known as the *Geometrical Product Specifications (GPS)* covering requirements of size and dimension, geometrical tolerance and geometrical properties of the surface (Fig. 1.1).

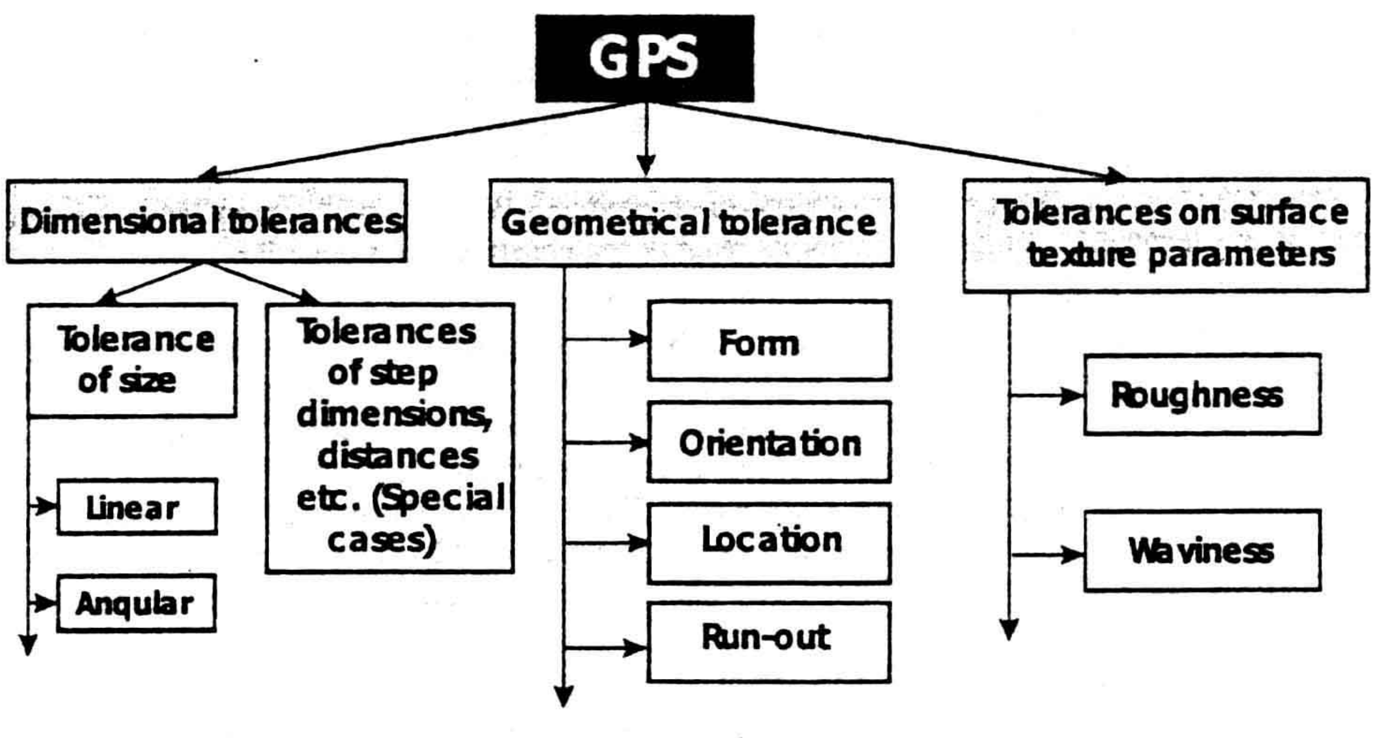

Fig. 1.1. General concept of *Geometrical Product Specifications.*

GPS are applied for various reasons. Generally – GPS give an assurance for obtaining some essential properties of the product:

- *Functionality*. A well-known example may be a machine tool – if its elements meet certain geometrical tolerances (e.g. straightness of bedways), the machine works well.
- *Safety*. If for example the crankshaft pin is ground according to specifications concerning roughness, there is no danger of a fatigue crack destroying the engine.
- *Dependability*. Properly selected geometrical tolerances, for instance roundness of compressor cylinders, guarantee long work life of the machine.
- *Interchangeability*. This is perhaps the oldest aspect applying GPS. Interchangeability is advantageous in assembly of a new machine and in repair as well.

It should be noted that GPS express different requirements in a language of geometry. The properties that are to be obtained using GPS are not necessary of a geometrical nature – the link between GPS and the desired parameters of a machine is indirect. It is down to the skill of the designer to "translate" the various mechanical requirements into the geometrical language of GPS. As an example a slide bearing may be considered – the relation of maximum and minimum clearances (that result from specified tolerances) to lubricating process is very complicated and difficult to foresee.

International organisations for standardization are deeply interested in developing the fundamentals of GPS. Technical Committee ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* was established in 1996 and works in close collaboration with a similar committee in the European organisation CEN/TC 290. According to *Vienna agreement* all projects are processed in parallel by these two technical committees – so documents on GPS prepared by ISO and CEN are identical.

The ISO/TC 213 runs the web site http://www.ds.dk/isotc213. This web site with partly open access gives the overview of the scope and activity of Technical Committee ISO/TC 213.

Most countries adopt international standards (ISO/CEN) on GPS by just issuing national standards which are identical to international standards; therefore ISO(CEN) standards obtain the status of their national standards. For countries that are members of CEN, implementation of European Standards through giving them status of national standards is obligatory.

The bases of GPS should be a part of mechanical engineering education. Each engineer that is involved in designing or manufacturing processes (even indirectly) must have some knowledge of specifications concerning the geometry of a product. Without such competence neither creating new technical documentation nor its reading and construction is possible.

In this textbook the contemporary idea of GPS has been presented in a concise form. First three chapters cover general information on GPS – standardisation and application in quality management. Chapters 4 – 19 may be regarded as the main part of the book – they contain a systematic review of different cases of tolerancing (based chiefly on *General GPS Matrix* – see Chapter 2) including their theoretical background. In Chapters 20 and 21 some specific methods of tolerancing (vectorial, statistical) are presented. The subject of Chapter 22 is calculation of tolerances applied in design and manufacturing. Chapters 23 and 24 cover inspection problems. Last chapters (25 – 28) concern selected questions related to standardisation, terminology and computer aided tolerancing.

The book contains many excerpts from standards, e.g. tables, examples of drawing indications etc. that can be applied in teaching process. It is strongly recommended in practical applications to use only full, original copies of the standards. The possibility of applying the most recent editions should be always investigated.

2 CHAINS OF GPS STANDARDS MATRIX MODEL

S. Białas

Before establishment of Technical Committee ISO/TC 213 *Dimensional and Geometrical Product Specifications and Verification* the need for classification of GPS standards was recognised. This was necessary for reviewing the many standards on GPS that were published before 1995, and for programming and monitoring future work in the field of GPS standardisation.

The Joint Harmonisation Group ISO/TC 3-10-57/JHG (working in years 1993 – 1996) prepared a Technical Report ISO/TR 14638:1995 concerning classification system of GPS standards, known as the *Masterplan*. In this document all GPS standards have been divided into 4 groups:

- Fundamental GPS standards;
- Global GPS standards;
- General GPS standards;
- Complementary GPS standards.

A special graphical presentation of these groups has been adopted (Fig. 2.1).

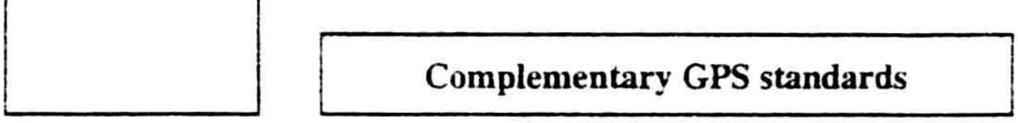

Fig. 2.1. Overview of GPS Masterplan structure.

According to the original idea, the group of *Fundamental GPS standards* should consist of such standards that establish very fundamental rules for dimensioning and tolerancing. However, in this group there are only two documents – ISO 8015:1985 (which, in fact, now is not regarded as really "fundamental") and ISO/TR 14638 which contains the outline of the *Masterplan*.

Global GPS standards are closely related to many other GPS standards – first of all those contained in the General GPS Matrix. Global standards influence general GPS chains of standards directly (being referenced to) or as default documents. The most important global GPS standard is ISO 1 on the standard reference temperature. Another global GPS standard is for example ISO 14660-1 which establishes terms and definitions of geometrical features. Several global GPS standards are under preparation. There are two metrological documents – VIM [2.1] and GUM [2.2] – that play an important role in GPS and for this reason may be found among the Global GPS Standards despite the fact that they are not standards.

Complementary GPS standards contain technical rules for drawing indications, definitions and verification principles for specific categories of features or elements. Some of the rules depend on the type of manufacturing process (machining, casting, welding, forming ...); other may concern the geometry of certain machine elements like screw threads, splines, or gears. Most of the numerous Complementary GPS standards have been prepared by various ISO Technical Committees; only a few are the results of TC 213 activity. Some complementary GPS standards are presented in Chapters 8, 18 and 19.

General GPS standards are the kernel of the *Masterplan*. They are ordered in a matrix in which rows constitute *chains* of standards, and columns concern various characteristics of geometrical features (Tab. 2.1). Due to the structure of this part of *Masterplan*, the whole system is known as the *GPS matrix model*.

Tab. 2.1. General GPS matrix – layout.

Chain link number / Geometrical characteristic of feature		1	2	3	4	5	6
1	Size						
2	Distance						
3	Radius						
4	Angle						
5	Form of line independent of datum						
6	Form of line dependent on datum						
7	Form of surface independent of datum						
8	Form of surface dependent on datum						
9	Orientation						
10	Location						
11	Circular run-out						
12	Total run-out						
13	Datums						
14	Roughness profile						
15	Waviness profile						
16	Primary profile						
17	Surface imperfections						
18	Edges						

A chain of standards consists of a set of standards related to a given characteristic. The standards are collected in a few groups – "links" of the chain. There are 6 chain links associated with different geometrical characteristics of features. There are explained as follows.

1. ***Product documentation indication – codification***. The standards placed in this link define drawing symbols (specific codes) and designations, establish rules of their application and explain how to read and generally understand specifications.
2. ***Definition of tolerances***. The standards contain theoretical definitions of tolerances and their numerical values as well (as translated from code symbols). By means of these standards theoretical exact features with associated tolerances can be defined.
3. ***Definitions of characteristics of actual (real) feature***. Basing on these standards, the geometry of a non-ideal, real workpiece can be unambiguously defined in relation to tolerance code symbols on the drawing. The definitions are based on a set of data points of considered features.
4. ***Assessment of the workpiece deviations – comparison with specified limits***. The main task of these standards is to state how to prove conformance or non-conformance of a real workpiece with specifications, taking into account the uncertainty of inspection procedures.
5. ***Measurement equipment requirements***. The standards in this link describe characteristics (particularly – metrological ones) of measurement instruments in a general approach or related to specific types of equipment.
6. ***Calibration requirements – measurement standards***. These standards establish the characteristics of calibration standards used in calibration procedures of the equipment described in link no. 5. The traceability to SI length unit (meter) shall always be assured.

It is clear then that each chain of standards is related to the complete process of designing (setting up unambiguous specifications), manufacturing (interpreting specifications) and verification (measuring).

Table 2.2 presents, as an example, the first row (chain of standards No 1) of the General GPS Matrix, concerning *size* – perhaps the most important characteristic of geometrical feature. (see Chapters 5 and 6). Some of the listed standards are in the course of preparation or revision.

Tab. 2.2. The chain of standards related to *size* – 1st row of General GPS Matrix.

1	2	3	4	5	6
ISO 129 ISO 286-1	ISO 286-1 ISO 286-2	ISO 286-1 ISO 8015 ISO 14660-2	ISO 14253-1	ISO 463 ISO 9121 ISO 9493 ISO 10360-1 ISO 10360-2 ISO 13225 ISO 13385 ISO 14253-1	ISO 3650 ISO 14253-1
Titles of the standards – see Chapter 28.					

The General GPS matrix is composed of a total of 6×18 = 108 cells (links of chains); each cell should contain at least one standard. The chain concerning *size* (Tab. 2.2) fulfils this requirement. However, many cells of other chains (e.g. the *distance* chain) are still empty because of the lack of corresponding standards. It is probable that after some years of activity of ISO/TC 213 all the chain links will contain related standards.

Fundamental GPS Standards

Global GPS Standards

General GPS matrix

Chain link number	**1**	**2**	**3**	**4**	**5**	**6**
Size						
Distance						
Radius						
Angle						
Form of line independent of datum						
Form of line dependent on datum						
Form of surface independent of datum						
Form of surface dependent on datum						
Orientation						
Location						
Circular run-out						
Total run-out						
Datums						
Roughness profile						
Waviness profile						
Primary profile						
Surface imperfections						
Edges						

Fig. 2.2. An example scheme explaining the indication of matrix cells in GPS Matrix model (ISO 5458).

The *Masterplan* applied as a tool in standardisation work helps to observe the following basic rules:

1. The *rule of unambiguity*; it means that each chain of standards in the General GPS Matrix shall contain all necessary, unambiguous regulations existing between the drawing indication and the geometrical characteristic of the workpiece, and that the assessed value representing the characteristic is traceable to international calibration standards. Each measurand in the chain shall be measurable.
2. The *rule of totality* – the standards contained in all chains (rows) of the General GPS Matrix shall ensure the possibility of indicating on the drawing all the required

characteristics. This rule influences the number of chains of standards in the General GPS Matrix. Up to now in the matrix there are enough chains of standard – but perhaps in the future some new chains will have to be added to the matrix, according to possible future needs.

3. The *rule of complementarity* – each of the individual chains of standards in the General GPS Matrix shall be complementary to the other. This means that individual requirements specified on a workpiece drawing are independent of each other and no interference occurs between them (e.g. between tolerances of size and of form).

Each GPS standard prepared by ISO/TC 213 contains an annex with the specific scheme that explains the position of the standard in the matrix model; the respective cell is marked (e.g. shadowed) on the scheme. In many cases the standard influences more than one chain link or even more chains of the matrix – therefore several cells may be marked. Fig. 2.2 presents an example of the GPS Matrix scheme concerning ISO 5458 (Positional tolerancing).

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2.3 Guide to the expression of uncertainty in measurement (GUM). International Organisation for Standardisation, 1993.